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Research and Development Technical Report

ECOM-0171-F

MILLIMETER WAVE SYSTEM ELECTROMAGNETIC COMPATIBILITY STUDY

FINAL REPORT

By
G.G. Sundberg
and
R.F. Marsolais

APRIL 1975

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MILLIMETER-WAVE SYSTEM EMC STUDY

Final Report

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DISTRIBUTION STATEMENT

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ABSTRACT

This report presents the results of a 12 month study program designed to obtain data on millimeter wave system electromagnetic compatibility characteristics. The period covered is from 6 February 1974 to 6 February 1975. Results described in the first three quarterly progress reports (references 1, 2 and 3) are summarized. Activities of the fourth quarter are described and recommendations for requirements of the millimeter wave electromagnetic compatibility specifications are included.

The millimeter wave electromagnetic compatibility study was performed with the objective of obtaining data which can be applied in establishing an electromagnetic compatibility specification for millimeter wave systems operating in the frequency range of 10 to 100 GHz. The effort was designed to investigate millimeter wave EMC problems, to recommend electromagnetic interference reduction techniques, and to update present miliary EMC specifications and standards to include millimeter wave systems.

An experimental program was conducted to collect data on EMC aspects of millimeter wave systems. This experimental program was designed to gather specific data which was found lacking in available millimeter wave literature which was reviewed during the literature search conducted in Phase 1 of the program. Data was collected on the levels and frequencies of spurious emissions, the relative levels of spurious response, radiated interference and radiated susceptibility. Millimeter wave coupling factors were investigated. These investigations included experiments on cable coupling and propagation, shielding and reflections of millimeter wave signals. Interference characteristics of modern state-of-the-art millimeter wave components were investigated.

Inter and Intra system EMC aspects of various millimeter wave systems were evaluated. Tests were performed to evaluate the unintentional electromagnetic interference characteristics of millimeter wave systems relative to other millimeter wave systems and other communication-electronics equipments and systems. The tests were designed to evaluate EMC between millimeter wave systems that may be located in the same enclosure and other systems that may be located within a radius of 100 meters.

An analysis program was conducted to support the experimental program. This analysis included the employment of a computer program to evaluate interference problems in typical millimeter wave system deployments. Other analysis consisted of an antenna out-of-band characteristic study, a millimeter wave filter study and a computer-aided spurious response analysis of typical millimeter wave receivers.

Recommendations submitted for specification limits were based upon the data and information collected during the study. These limits included such requirements as system radiated emissions and susceptibilities, transmitter spectra, receiver spurious responses, conducted interference and susceptibility, acceptance bandwidth and emission bandwidths. Recommendations were also made for testing methods and test instrumentation requirements.

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I. INTRODUCTION AND SUMMARY

This study was performed for the purpose of obtaining information on electromagnetic compatibility (EMC) characteristics of millimeter wave systems. The results of this study provide a basis for establishing recommendations for requirements to be incorporated into a millimeter wave EMC specification. This study has accomplished the required task through implementation of the following program:

1. Literature search reviewing the status of present day millimeter wave systems and components.

2. Review of present electromagnetic compatibility requirements and characteristics of millimeter wave systems.

3. Analysis of interference problems unique to millimeter wave systems.

4. Performance of experiments designed to evaluate susceptibility and emission characteristics of millimeter wave systems and components.

5. Performance of experiments designed to investigate the propagation and coupling characteristics of millimeter waves.

6. Analysis of specific areas affecting EMC aspects of millimeter wave systems such as modulation effects and antenna out-of-band characteristics.

7. Investigation into the design of a developmental EMI receiver exhibiting improved testing capabilities over presently available millimeter wave EMI instrumentation.

8. Interference prediction simulation of millimeter wave systems and other systems collocated within a radius of up to 100 meters in typical deployment configurations.

9. Establish recommendations for susceptibility and emission limits and test methods to extend the requirements of MIL-STD-461, 462 and 469 to include millimeter waves.

Results of experiments and analysis performed to obtain information on millimeter wave interference problems are summarized. Interference predictions relative to millimeter wave systems deployments planned by the Army are obtained from the interference prediction computer program developed for this study. Results of the interference prediction program have provided an effective means of obtaining a meaningful perspective of the overall interference environment in typical deployments. Interference susceptibility and emission characteristics of millimeter wave systems obtained during the experimental and theoretical investigations of the study program are utilized as input data to the interference prediction program.

Extensions of MIL-STD-461, 462 and 469 are recommended. Additions of new requirements and modifications of present requirements are included. The recommendations are based upon a review of the overall results obtained during the study. Characteristics of equipment and techniques associated with millimeter wave systems including modulation effects, antenna characteristics, equipment limitations, and propagation aspects of millimeter waves are included. The recommended requirements are directed towards millimeter wave systems collocated with other systems within a distance of 100 meters.

This final report includes experiments performed in the fourth quarterly period. Details of analysis programs conducted for the purpose of evaluating modulation effects and antenna out-of-band characteristics are included. The major portion of this report is directed toward obtaining the recommendations for limits, requirements, test methods and instrumentation. Summaries of study results of the three quarterly progress reports are included. The recommendations are based upon the technical aspects of the results obtained during the experimental and theoretical effort of this study. No attempt has been made to lessen the requirements to meet the limitations of presently available millimeter wave EMC test equipment. Results of experiments and analysis performed during this study indicate that test equipment can be developed to meet the requirements recommended in this report.

Test proeedures which were described in the quarterly reports were designed to obtain meaningful data with the most cost-effective approach. These test methods employed techniques which were most simply executed without compromising the quality or intent of the test.

A. FIRST QUARTER

The first quarter effort was directed primarily toward conducting a thorough search of available literature containing pertinent information on millimeter wave systems and components.

1. K_a Band Communication System

Charactertistics of a K_a band communication system were studied during this literature search. This system employed a low noise circuit employing IMPATT diodes as local oscillators for balanced mixers. The system has the capability to operate in full duplex narrowband (voice) and broadband (analog/digital) modes. Susceptibility aspects in the form of error-causing mechanisms of the transmission media are described. Noise performance of the IMPATT oscillator is described.

2. Millimeter Wave Experiment

An electromagnetic interference test program conducted on a spacecraft millimeter wave experiment was studied. This testing plan was designed to provide sufficient data to make an assessment of the EMI compatibility between the millimeter wave system and other spacecraft systems. Conducted interference tests were based on a total noise requirement not related to MIL-STD-461 requirements. The spacecraft equipment was designed to operate successfully with a 10 millivolts peak to peak level on a powerline with 0.1 ohm impedance.

Conducted susceptibility tests were performed in general accordance with MIL-STD-462 methods CS01 and CS06. The impressed signal levels however were modified from the MIL-STD-461 values to levels more compatible with the expected performance of load interface circuits. Conducted susceptibility levels of 10 millivolts peak (without regard to frequency) and ±2 volt transients having total energy levels of 30 millijoules maximum were found to be representative of typical conditions existing within the spacecraft. MIL-STD-461 limits for conducted susceptibility test levels represented an over test condition for the spacecraft environment. Radiation emission tests were performed per method RE02 of MIL-STD-462. Conducted emission CE02 and CE04 were not performed since compatibility tests were performed to provide assurance that signals on control and signal lines were compatible with the spacecraft equipment. Compliance to CE06 and RE03 was verified by individual testing of the special filters installed in the transmit waveguide. RS03 was performed per MIL-STD-462 requirements. A susceptibility problem was discovered at 10 MHz. This susceptibility condition was improved by completely shielding the cable between the RF multiplier unit and the modulator/power amplifier unit. Although the system did not meet RS03 requirements the problem was alleviated sufficiently to provide compatible operation within the spacecraft environment.

3. 60 GHz Monopulse Radar

A 60 GHz monopulse radar planar-array was analyzed. Test results were described. A gain of 31.0 dB was measured. The E-plane beam width was 2.7 degrees the H-plane beamwidth was 2.8 degrees.

4. 60 GHz Communication System

An experimental 60 GHz battery powered communications data link was described. This radio set has the capability to handle any video signal such as TV or composite multiplexed data occupying a baseband of 5 Hz to 10 MHz.

5. Millimeter Wave Components

Several reports were described which address various millimeter wave components such as transmitting devices, mixers, antennas, vacuum tubes, low-noise millimeter wave amplifiers, parametric pumps and other IMPATT devices.

6. Atmospheric Attenuation

A report on an analysis of zenith attenuation measurements of the atmosphere on both sides of the oxygen absorption spectrum (48 to 72 GHz) was described. The Gross, Lorentz and Van Vleck–Weisskapf theories are compared with experimental results.

7. 35 GHz Transmitter

A document containing specifications of a 35 GHz transmitter system was described. Characteristics such as stability, spurious signals, bandwidth, modulation, gain, and sideband power are discussed.

8. 381 H Backward-Wave Oscillator

Data on type 381 H Backward-Wave Oscillator was included. This device is capable of producing a CW output power of more than 5 watts over the frequency range of 51 to 55 GHz. Intermodulation and noise power output characteristics are described.

9. 60 GHz Power Amplifier Combiner

Development of a 60 GHz Power amplifier/combiner was described. This development obtains CW output power of 3 watts using IMPATT devices Bandpass characteristics are discussed.

10. Anti Window Frequencies

A report describing the use of the anti-window (high attenuation frequencies) of the millimeter wave region is discussed for use in secure communications.

11. K Band Repeater

The midterm progress report on a K band repeater exploratory development contract is described in detail. This report contained data on intermodulation products and antenna characteristics.

12. Proposed Calibration Test Set

Requirements of a proposed calibration test set standard is described in a purchase description issued by the Hughes Directorate of Metrology. This test set shall provide CW and swept measurement capabilities over a frequency range of 50 to 75 GHz. It shall consist of a power supply, RF plug-ins and required auxilliary equipment to make a complete millimeter CW and swept measuring system. Shielding of the test set shall meet MIL-STD-461A requirements. Radiated power of the signal source shall be less than -80 dBm at a distance of 12 inches from the source.

B. SECOND QUARTER

Military Standards MIL-STD-461, 462 and 469 (references 10, 11 and 12) were reviewed to determine the most pertinent type of data that should be gathered during the experimental program. Communication and radar systems were considered the most prominent types of systems to be investigated.

Typical causes of interference were considered. Familiarity with the system components which represent the major source of interference problems was considered important in determining the most practical test procedures and types of limits to be included in the millimeter wave EMC specification.

Mechanisms of unwanted output generation in transmitters were investigated. These outputs include harmonics, sideband splatter, and other spurious outputs. Receiver susceptibility characteristics such as intermodulation products and spurious responses were investigated.

Typical millimeter wave mixers were described. The importance of control in production techniques in controlling interference characteristics was stressed.

Typical antennas, mixers and receivers available for use as portable millimeter wave EMC test equipment were evaluated. It was found that improvements are needed in areas of sensitivity, built-in calibrators, frequency read out and spurious responses. Further development in EMC test equipment is required before successful recommendations can be made for integration of test equipment into a military EMC specification.

The primary emphasis of the second quarter was performance of experiments designed to gather data necessary to evaluate the interference characteristics of millimeter waves, systems and components. Data was gathered to be used in establishing recommendations for specification limits and test requirements in the frequency range of 10 to 100 GHz. An analysis program was also undertaken to aid in the analysis of data as pertaining to EMC conditions in typical deployments.

The following paragraphs summarize the nine experiments and the three computer analyses.

1. Susceptibility of Millimeter Wave Detectors

Experiment one was designed to test millimeter wave detection components and evaluate intermodulation characteristics, rejection of unwanted signals and crossmodulation characteristics. MIL-STD-461 and MIL-STD-462 test methods and requirements were employed as guidelines. IMPATT diode sources were employed as test signal generators. The detectors evaluated in the second quarter were single ended devices. Considerable variations were found among millimeter wave devices. The experiment clearly indicated the importance of quality control in manufacturing of millimeter wave devices. Substandard millimeter wave devices displayed poor susceptibility characteristics.

2. A Basic Test Set-Up

Experiment two consisted of devising a simple equipment test set-up to measure frequency and relative amplitude of millimeter wave signals. This was accomplished by using standard test components. A millimeter wave transmitter was checked for bandwidth characteristics using an oscilloscope, a millimeter wave detector and two millimeter wave absorption type wave meters.

3. 60 GHz Transceiver

Experiment three evaluated a 60 GHz communication system consisting of two transceivers for susceptibility to an interfering signal. These transceivers used a frequency sweep circuit to lock on to the desired signal. It was found that a system of this type easily rejected the interfering signal. Millimeter wave systems employing automatic frequency lock circuits such as this should meet susceptibility requirements such as those specified in MIL-STD-461.

4. Susceptibility Test of a 60 GHz Communication System

Experiment four was designed to evaluate test method RS03 of MIL-STD-461 as applied to millimeter wave systems. A 60 GHz signal at a level of +17 dB was fed into a 10 dB gain antenna and radiated at the transceivers. The 60 GHz radiated signal was directed toward the power leads and receiver components while operation of the receiver was monitored. There was no noticeable deterioration in the system operation except for a 1000 Hz tone which was detectable in the audio output. This tone was being coupled via power leads and was independent of the 60 GHz susceptibility signal. This also indicates the necessity for conducting lower frequency susceptibility tests on millimeter wave systems which are displayed with low frequency systems.

5. Millimeter Wave Coupling

Experiment five was devised to determine if millimeter wave signals could be coupled onto a power cable. The cable used was a single unshielded conductor. Sweep generators and spectrum analyzers were used to generate and monitor any signals. Using such equipment, it was not possible to couple any signals of 30 GHz or above onto cables via radiation. This experiment indicates that it would not be practical to perform cable conducted susceptibility tests at millimeter wave frequencies. No other coupling methods other than radiation were found to be available for this experiment.

6. Cable Propagation

Experiment six monitored the propagation characteristics of high frequency (300 MHz) signals present on power cables. This experiment verified that amplitude attenuation per unit length at these frequencies is proportional to the wavelength of the signal. An attenuation of approximately 20 dB per wavelength was noted.

7. Filter Characteristics

Experiment seven was conducted to determine filter characteristics at 90 GHz. State-of-the-art techniques and the latest filters were used. It was found that filter characteristics similar to those of lower frequency microwave

filters are obtainable at millimeter wave frequencies. Precise control of the filter fabrication technique becomes increasingly difficult however at the higher frequencies.

8. Mixer Sensitivity

Experiments eight and nine were conducted to measure the sensitivity of various available mixers. It was found that there was considerable variation in the available units, ranging from -18 dBm to -80 dBm. Test frequencies ranged from 34 to 94 GHz.

9. Analysis

An analysis program was also conducted to aid in data acquisition and analysis. Computer programs were written for each analysis. Analysis number one was a method of describing emission spectra envelope of a pulsed transmitter. The Electromagnetic Compatibility Analysis Center (ECAC) method was used.

Analysis two was a computer program designed to predict possible spurious response in millimeter wave systems. Standard formulas were used.

Analysis three was a program designed to predict a total communication system response at all desired frequencies. The program took into account antenna characteristics, propagation losses, and spurious outputs and responses in the total system. At the end of the second quarter, this program was still being developed. It was finished in the third quarter.

10. Conclusions

As a result of the second quarter effort, a closer familiarity with millimeter wave characteristics was obtained. Knowledge of interference susceptibility of typical millimeter wave components was obtained. Typical communication systems were tested for interference characteristics. Preliminary analysis of MIL-STD-461 and MIL-STD-462 as applied to millimeter wave systems and electromagnetic compatibility aspects of typical millimeter wave deployments was initiated.

Millimeter wave filters are an area where progress is taking place in the state-of-the-art. All millimeter wave filters are distributive in nature and due to technological restrictions are limited to three classes: waveguide, stripline and microstrip. Due to equipment availability, most filter work has been done in the Ka-band (26.5-40 GHz).

Hughes has developed two types of millimeter wave filters; the coaxial line filter and the direct coupled cavity bandpass filter. The direct coupled cavity filter can be tailored to either a Chebyshev or Butterworth response, being either a rectangular cavity operated in the TE_{101} mode or a cylindrical cavity in the TE_{011} mode. A typical quality factor Q for each type is 10,000 for the cylindrical cavity and 3100 for the rectangular cavity. These values are very dependent on the manufacturing processes used.

C. THIRD QUARTER

Experiments from the second quarter were continued for the purpose of evaluating millimeter wave characteristics. The analysis program was also continued, with further analysis on total millimeter wave systems involving both communications and radar equipment.

Experiments were designed to collect data on shielding and reflection properties of various materials, monitor collocated millimeter wave system performance, measure interference radiations, evaluate millimeter wave compatibility characteristics, and measure high order harmonic outputs of lower frequency systems in the 1.0 to 10 GHz frequency range.

A preliminary test matrix was drawn for the expansion of MIL-STD-461, 462, and 469 into the millimeter wave frequency range (10 to 100 GHz). The preliminary data indicates certain tests can be omitted and others relaxed. This is because of the propagation and coupling characteristics of electromagnetic waves at millimeter wave frequencies.

Equipment such as accurate generators, sensitive receivers, and accurate frequency measuring equipment are not commercially available at these frequencies. For this reason, data is often difficult to gather and difficult to measure. This poses a serious problem to performing EMC tests in the millimeter wave frequency range at the present time.

1. Shielding and Reflectivity

Experiment ten was performed to investigate the shielding and reflectivity characteristics of building and equipment enclosure materials. (Experiments one through nine are described in the second quarterly report). The need for this experiment became obvious in the course of the second quarter's experiments when waves were found to be shielded or reflected by materials not posessing these properties at lower frequencies. Building materials tested were: cement, wood, and brick. Equipment enclosure material tested was RF absorbent foam.

Briefly summarized, the test revealed most of the materials to be frequency sensitive. Shielding and reflectivity properties went from low to high or high to low depending on the frequency and the material being tested. It was found that common building materials such as brick, wood or concrete could provide considerable shielding at higher millimeter wave frequencies.

2. Radar/Communication Compatibility

Experiment eleven was conducted to evaluate the interaction of a 94 GHz millimeter wave radar and a 60 GHz communications system. It was found that these systems could be operated in close proximity to each other without discernable deterioration in performance, with the exception of operation in the main beam.

3. Radar EMI Emissions

The next experiment, number twelve, measured the field around a millimeter wave radar. This experiment was performed by placing a pick-up probe at various points around the 94 GHz radar antenna. It was found that all

significant E and H plane radiations were contained in an area of ±2.5 degrees. All sidelobes and the main beam were very narrow, all less than 0.5 degree (3 dB points). This experiment showed the main beam and major sidelobes to be contained in a narrow ±2.5 degree beam.

4. Ka Band Communications System

Experiment thirteen was designed to evaluate the interference characteristics of a Ka band communication system. Measurements performed during this experiment included radiated emissions, spectrum evaluation, and compatibility tests. Radiated emissions from the case and wave guides were measured. Second and third harmonics were evaluated. Compatibility tests consisted of operation of a collocated 60 GHz communication system during simultaneous operation of the Ka band system.

The tests revealed that the major radiated emissions from the millimeter wave communication systems outside of the main transmit beam were found in the major sidelobes, around waveguide flanges and from reflections in the test area. Proper enclosure shielding reduced the waveguide flange emanations to a negligible value. Numerous materials possess a high reflectivity coefficient at millimeter frequencies and can provide interference problems at these frequencies.

Radiations at distances of 10 to 100 meters were of relatively low levels and compatible operation of collocated adjacent channel systems could be obtained if the enclosures are shielded and if reflections of the main beam and the major antenna sidelobes are avoided. Measurements performed during this experiment indicate that compatible operation can be obtained if enclosure radiations at a distance of one meter are limited to levels of less than 0.1 volts per meter (100 dB/uV/meter). This would be equivalent to a value of 80 dB/uV/meter at a distance of 10 meters.

Harmonics and spurious emissions of this system were below the sensitivity of the EMI instrumentation. Analytical estimates of the harmonics indicate the harmonics are at least 60 dB below the fundamental. If operation of collocated communication systems are planned to operate at frequencies harmonically related to other communication systems a value of 60 dB down from the fundamental should be imposed on millimeter wave systems. An alternate method would be to restrict harmonic radiations to a specific level, which would require greater suppression of harmonics in high power systems.

5. High Order Harmonics

Experiment fourteen was designed to provide data which would be helpful in establishing compatibility test criteria for millimeter wave systems operating in the 1.0 to 10 GHz region. The harmonic output of these systems was measured to see if there was sufficient output in the 10 to 100 GHz region to cause interference of collocated systems. It was found that some systems had sufficient output up to the tenth harmonic to cause susceptibility problems. This experiment suggests the necessity of compatibility tests for 1.0 to 10 GHz systems that are to be operated around higher frequency systems. An alternate approach would be to impose test requirements up to the tenth harmonic on these systems.

6. Analysis

The analysis program was designed to evaluate modulation effects, out-of-band antenna characteristics, and multiple collocated system performance. Analysis one and two are described in the Second Quarterly Summary.

Analysis three was performed for the purpose of describing emission spectrums of millimeter wave systems employing state-of-the-art high data rate modulation processes. Particular emphasis was made on a modulation method known as continuous phase shift modulation (CPSM) (Reference 4). This analysis indicates that the modern state-of-the-art modulation techniques employed in high data rate systems exhibit inprovements in interference emission and susceptibility characteristics over earlier techniques. These newer methods also have less energy in their sidelobes, resulting in less adjacent channel interference.

Analysis four was intended to analyze the performance of millimeter wave antennas of the horn variety at frequencies higher than their intended frequency of operation. This analysis originally started as an experiment but when the complexities of the performance of this experiment became obvious, an analytical approach was resorted to.

This analysis revealed the millimeter wave horn antenna as having essentially high pass characteristics. Below its intended frequency of operation, the horn exhibits rapid attenuation. Above the cutoff frequency, the gain fell off approximately 2 dB per octave from its peak gain.

The final analysis of this quarter, number five, was a computer analysis designed to evaluate an environment containing several transmitters and receivers. This program will give the frequencies and amplitudes of the interfering signals. The results of this analysis will be used to establish radiated emission and susceptibility requirements for the millimeter wave EMC specification.

By combining the results of the second and third quarter, a better picture of the millimeter wave EMC situation was obtained. This final picture is presented later in this report.

D. FOURTH QUARTER

The major portion of the fourth quarter effort consisted of performance of analyses of data, millimeter wave components and system characteristics and establishing recommendations for the millimeter wave EMC specification. Some experimental effort was expended in certain areas where further definition of millimeter wave characteristics was deemed necessary to provide more detailed definition of EMC requirements.

Analysis performed included the millimeter wave experiment, the antenna out-of-band characteristics, the millimeter waveguide filter and typical Army deployment analyses. These analyses are described in detail in Section III of this report.

Experiments performed during this quarter included a follow-on of experiment numbers one, five and thirteen. An experiment consisting of evaluation of a balanced mixer was performed to provide a comparison with the single ended mixer evaluated in experiment one (reference 2). Further investigation of millimeter wave coupling was performed as a follow-on of experiment number five (reference 2). The Ka band system tested in experiment number thirteen (reference 3) was evaluated further to determine its receiver characteristics.

1. Balanced Mixer Evaluation

A balanced mixer was evaluated using the test set-up shown in Figure 1.

a. Test Equipment

Nomenclature	Manufacturer	Model No.
RF 1 (Impatt Diode)	Hughes	—
RF 2 (Impatt Diode)	Hughes	—
LO (Local Oscillator)	Varian	VRE-2103B
Attenuator	Hitachi	M1513
Attenuator	TRG	V510
Isolators	Hughes	—
Balanced Mixer	Hughes	—
Spectrum Analyzer	Hewlett Packard	850
Power Meter	Hewlett Packard	—

The balanced mixer was evaluated to compare intermodulation and sensitivity characteristics in comparison to the single ended mixer evaluated in experiment number one.

b. Test Procedure

Sensitivity

The sensitivity was measured by determining the minimum discernible signal (MDS) on the spectrum analyzer display. Power output of the signal source required to produce the MDS was then measured on the power meter. This value of power was considered as the mixer sensitivity.

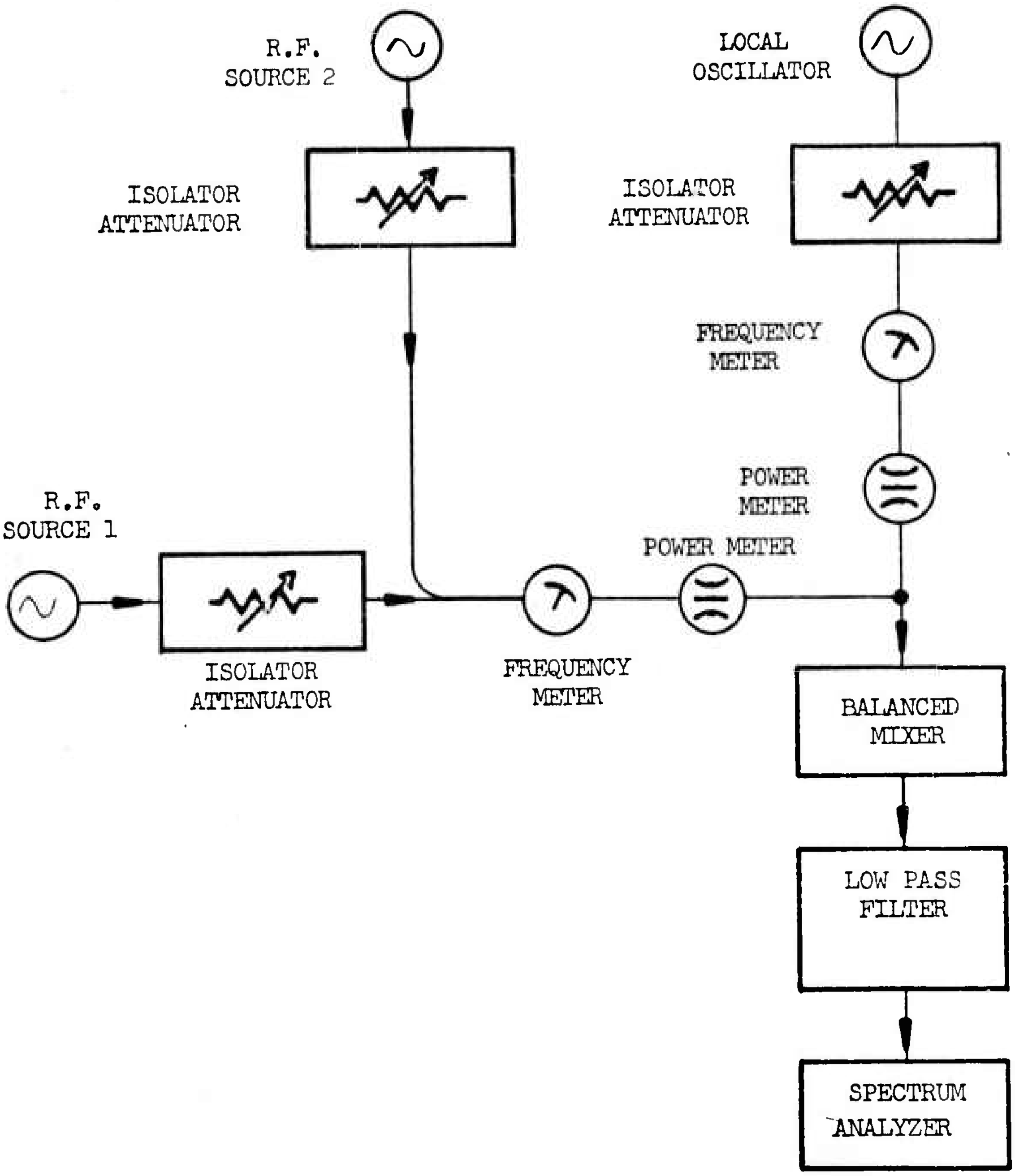


Figure 1. Test Set-up for Balanced Mixer Evaluation

Intermodulation

Two frequencies F1 and F2 were chosen which would produce third order intermodulation products which would fall in the bandpass of the low pass bandpass filter and appear on the spectrum analyzer display. Frequencies chosen for this experiment were as follows:

Local oscillator	= 59. 8 GHz
F1	= 60. 16 GHz
F2	= 60. 3 GHz

The third order modulation is produced by the following frequencies:

2 F2 - F1 - LO
2 (60. 3) - 60. 16 - 59. 8 = 0. 64 GHz

2 F1 - F2 - LO
2 (60. 16) - 60. 3 - 59. 8 = 0. 22 GHz

These frequencies appeared on the spectrum analyzer display which had a bandpass of 2. 0 GHz. The responses disappeared when either F1 or F2 was eliminated, indicating that these responses were due to intermodulation products in the mixer.

c. Test Results

Sensitivity

The balanced modulator exhibited an improvement of approximately 10 dB over the single ended mixer evaluated in experiment number one. A sensitivity of -90 dBm was measured as compared to -80 dBm obtainable in single ended mixers.

Intermodulation

The balanced mixer did not display any appreciable improvement in intermodulation characteristics as compared to the single ended mixer of experiment number one. Both mixers indicated intermodulation products of approximately 30 dB below the fundamental.

d. Conclusions

The balanced mixer will provide greater sensitivity than a single ended mixer; however, the balanced mixer did not provide any appreciable improvement in intermodulation characteristics. Further investigation of balanced and double balanced mixers was performed in a literature search. This investigation revealed that it is necessary to employ double balanced mixers to obtain any appreciable improvement in intermodulation characteristics. Data published in the articles of reference numbers 14 and 15 indicate that a balanced modulator should theoretically show a improvement of 6 dB and a double balanced mixer should have an improvement of 12 dB over a single ended mixer.

2. Millimeter Wave Coupling

A millimeter wave coupling experiment was performed on coaxial cables. The objective of this experiment was to determine whether millimeter waves could be advertently coupled onto coaxial cables. A worst-case situation was simulated with an open ended coaxial cable terminated in an unshielded loop of wire. The loop was exposed to a 20 GHz radiated signal. A millimeter wave receiver was connected to the opposite end of the coaxial cable. RG8/U coaxial cable was used in this experiment.

a. Test Equipment

Nomenclature	Manufacturer	Model
Signal Generator	Hewlett Packard	628
Millimeter wave receiver	Micro-Tel	WR-250

b. Test Procedure

An RG8/U coaxial cable was terminated in a loop of wire and exposed to a 20 GHz radiated field as shown in Figure 2.

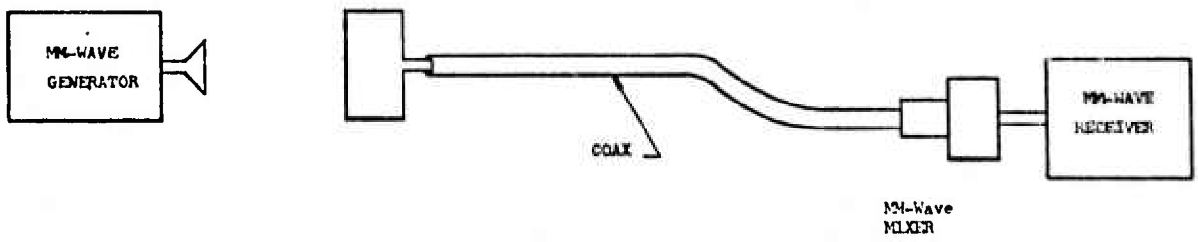


Figure 2. Test Set-up for Cable Coupling Experiment

The radiated field produced by the millimeter wave generator was measured to establish the reference level for determining the attenuation of the cable. This field was found to be approximately 80 dB above the tangential sensitivity of the receiver. It was necessary to provide extra shielding of the mixer assembly.

c. Test Results

No evidence of a coupled signal could be detected.

d. Conclusions

Results of this follow-on effort of experiment number five has provided further evidence that millimeter waves are not readily coupled onto cables. This experiment provides further rationale for the elimination of cable susceptibility testing at millimeter wave frequencies.

3. Ka Band System Evaluation

Further evaluation of the Ka band millimeter wave system was performed during the fourth quarter. This evaluation was performed in conjunction with development and demonstration tests performed for the customer on the Ka band program. Sensitivity, dynamic range and spurious response characteristics of the Ka band system was obtained from test results obtained during various stages of the Ka band system development. The spurious response characteristics were obtained by evaluating the balanced mixer employed in the system.

a. Test Equipment

Nomenclature	Manufacturer	Model No.
Impatt diode source (2)	Hughes	—
Frequency meter	FXR	U410F
Attenuator	TRG	V510
Power meter	Hewlett Packard	432A
Filter	Hughes	—
Spectrum analyzer	Hewlett Packard	8551

b. Test Procedure

Figure 3 shows the basic test set-up used during evaluation of the Ka band system.

Sensitivity

The IF output of the Ka band system was monitored to determine the tangential sensitivity. The minimum detectable level was noted on the spectrum analyzer connected to the IF output. Output of RF source number one necessary to produce this response was measured on the power meter.

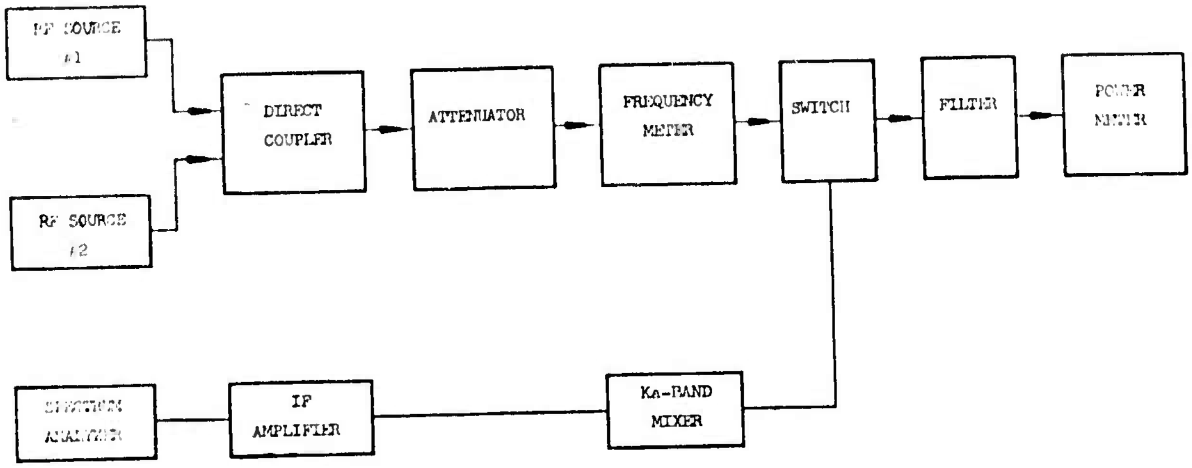


Figure 3. Ka Band System Test Set-Up

Dynamic Range

Output of RF source number one was increased until the output of the Ka band system began to indicate non-linear response. The power output of the RF source was measured on the power meter and compared to the power output required to produce the minimum discernible signal of the Ka band system.

Spurious Response

RF source number one was set at a power output level necessary to produce a standard response. RF source number two was set at a level equal to approximately 60 dB above the minimum discernible signal. RF source number two was then scanned through out-of-band frequencies above the waveguide cut-off frequency. Spurious responses were observed on the spectrum analyzer. Spurious response levels were determined by reducing RF source number two output to the point where the spurious response disappeared on the spectrum analyzer. This RF source output was measured on the power meter.

c. Test Results

Sensitivity — -90 dBm
Dynamic Range — 60 dB
Spurious Response — 40 dB below fundamental

d. Conclusions

Results obtained during evaluation of the Ka band system indicate that it exhibits typical values of sensitivity, dynamic range and spurious response for systems employing balanced mixers.

II. ESTABLISHMENT OF STUDY APPROACH

A. ORGANIZATION OF STUDY

This millimeter wave EMC study was organized to gather information on the trend of advancement in the state-of-the-art of millimeter wave systems and components as applied to interference characteristics. This information was used as a baseline in developing the millimeter wave EMC standard. Basically the study was directed toward obtaining information that would be applicable to collocated systems operating within a distance of up to 100 meters. The information gathered was in many instances also applicable in a more general nature and can be extrapolated in establishing interference criteria for systems at any distance.

The study effort was grouped into three phases. Phase one consisted of a literature search. Approximately 200 reports were reviewed with the objective of obtaining information on millimeter wave system relating to their interference characteristics. Phase two consisted of the experimental portion of the program. Experiments were performed which provided emission and susceptibility data on millimeter wave systems. The analysis portion of the study and development of the EMC specification test limits and methods were accomplished during Phase Three.

Planning of the study program included obtaining the type of information which would be helpful in establishing meaningful interference tests and practical limits for emissions and susceptibilities of millimeter wave systems. The proposed tests and limits are designed to be patterned to present existing standards whenever possible. The attempt is made to extend test limits and methods of the present day standards MIL-STD-461, 462 and 469 to include the frequency range of 10 to 100 GHz. Economic factors are considered in the establishment of EMC test requirements in the new standard recommendations.

Recommended tests are designed to avoid complexity in test setups and to strive for simplicity to as great an extent as possible without compromising the quality of test results.

The computer-aided analysis program developed for this study utilized a combination of mathematical models of typical millimeter wave transmitters and receivers and empirical data obtained during the experimental phase and literature search. Portions of the computer program was based on prior work performed by Jansky and Bailey (reference 5).

The analytical effort was designed to support the experimental program in obtaining pertinent information to be employed in defining interference characteristics of millimeter wave systems. The interference prediction computer program was designed to provide interference interactions between simulated millimeter wave and other collocated systems. Reference 5 was employed as a guideline in the development of this program. Other computer programs were used to predict spurious responses of typical millimeter wave receivers. An antenna analysis was performed to define out-of-band characteristics of millimeter wave systems. An analysis of modulation techniques employed in modern millimeter wave systems was performed to determine interference spectra of

transmitted emanations produced by these types of modulations. Reference 4 was employed as a guideline in evaluating the effects of modulation on susceptibility of systems.

B. CHARACTERISTICS OF MILLIMETER WAVE SYSTEMS

The Millimeter Wave EMC Study Phase I literature search indicated that electromagnetic interference characteristics of millimeter wave systems are similar to lower frequency systems in some instances such as in areas of broadband emissions and susceptibilities. These emissions and susceptibilities represent the low frequency components of interference spectra that are a function of components such as modulators, power supply inverters and control circuits. However, the interference characteristics of millimeter wave systems at their operating frequencies differ in some respects from lower frequency systems.

Interference characteristics of millimeter wave systems differ from lower frequency systems mainly due to the different behaviour of the extremely short wavelengths. These differences occur mainly in parameters such as propagation and coupling. Other differences are due to inherent interference characteristics which are a function of unique construction techniques employed in millimeter wave components and systems. Modulation techniques employed in modern millimeter wave systems also influence their interference characteristics due to the wide bandwidths required to accommodate the high data rates employed in these systems.

Results of the literature search (reference 1) and experimental program (references 2 and 3) indicate that millimeter wave systems characteristics are rapidly improving with advancement of the state-of-the-art in quality control of components. These advancements are manifested in improvements of millimeter wave system performance in areas such as signal to noise ratios, sensitivity, dynamic range, intermodulation distortion and stability. These advancements have resulted in improvements in interference susceptibility characteristics of modern millimeter wave systems. A basic modern millimeter wave receiver design is shown in the block diagram of Figure 4. Mixer and local oscillator operational parameters represent the most critical receiver design areas in obtaining satisfactory interference characteristics in millimeter wave receivers.

Performance of electromagnetic interference measurements during the experimental phase of the study revealed shortcomings in presently available millimeter wave EMC test equipment. Characteristics of a receiver being developed for application on a space program which represents the modern state-of-art in millimeter wave receivers is described in Section V-B of this report. This receiver represents the required level of control in functional characteristics and operational configuration of an EMC receiver capable of successfully performing the measurements necessary to obtain the data which will assure compliance to the millimeter wave EMC specification.

Details on the information gathered during Phase I of the study is contained in the First Quarterly Progress Report (reference 1). Table I contains an EMI test results summary on a typical millimeter wave system which operated satisfactorily in its intended application. From the results shown in Table I it is quite evident that the system did not meet the low frequency

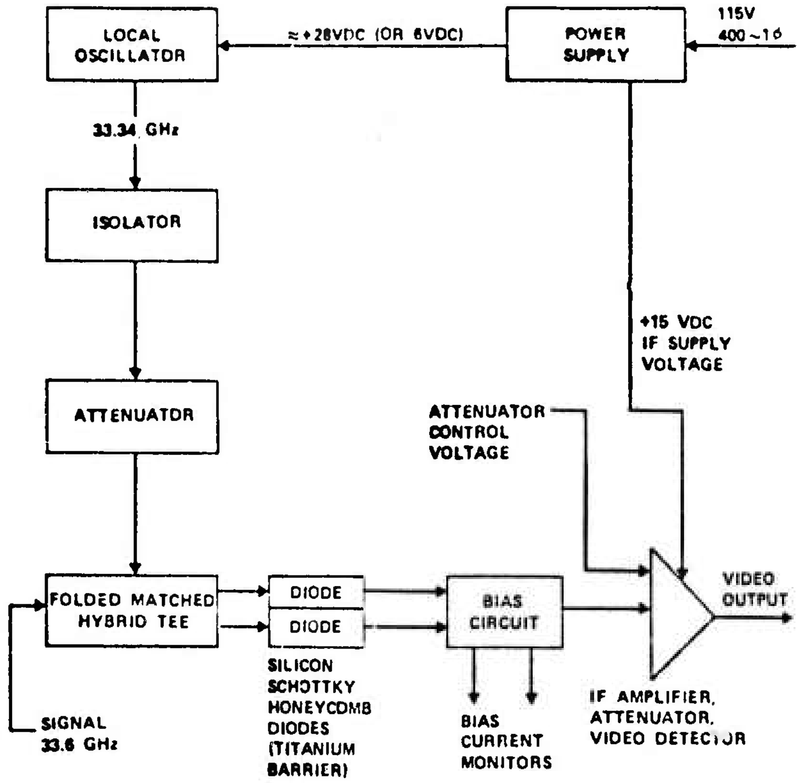


Figure 4. Receiver Block Diagram

requirements of MIL-STD-461A. The literature search revealed that EMC tests on millimeter wave systems are in most part limited to the present MIL-STD-461A frequency range of 30 Hz to 10 GHz. These tests are therefore meaningful only when the millimeter wave system is planned for deployment with collocated low frequency systems. The data in Table I also indicates that the EMC design requirements need not be as stringent in a millimeter wave environment as evident by the fact that this system operated satisfactorily in such an environment although it did not comply with MIL-STD-461A.

Although this study was basically concerned with separation distances of up to 100 meters it is interesting to note the atmospheric attenuation chart in Figure 5. The chart shows that the attenuation is negligible at the distances considered in this study, however it indicates the reasons for the high millimeter wave activity at 30 GHz (window), 60 GHz (anti-window) and 90 GHz (window). The V band (60 GHz) operations are devoted primarily to those systems where transmission beyond a specific distance is not desired.

TABLE 1. EMI TEST RESULTS SUMMARY

Test Method	Emissions or Susceptibility Which Exceeded MIL-STD-461A Limits
Conducted emission CE01	LIC 1 bus, 7.2 dB above limit at 8.67 KHz LIC 1 return 10.1 dB above limit at 8.62 KHz 6.4 dB above limit at 8.86 KHz 1.6 dB above limit at 17.3 KHz
Conducted emission CE03	LIC 1 return, 9 dB above limit at 5 MHz
Conducted susceptibility CS01	LIC return lines, some degradation at 30 to 40 mv peak-to-peak applied signal
Conducted susceptibility CS06	No effect noted
Radiated emission RE02	All modes, 10 MHz 2 dB above limit Communications mode, initial problem at 150 MHz corrected by improved test setup Multitone mode 180 MHz 22.7 dB above limit 360 MHz 4.3 dB above limit 540 MHz 3.1 dB above limit 720 MHz 1.5 dB above limit
Radiated susceptibility RS03	Interference threshold 20 dB below limit at various frequencies from 10.5 MHz to 180.0 MHz Initially 40 dB below limit at 10.2 MHz After shielding 20 dB below limit at 10.2 MHz

C. SELECTION OF PERTINENT DATA

Analysis of data on characteristics influencing interference properties of millimeter wave systems gathered during the experimental portion of the study verifies that interference problems will be less severe than at lower frequencies. There are several reasons causing this condition. One of the major reasons is that millimeter wave signals are almost always directed into very narrow radiated beam widths. Therefore, an interference causing condition can usually be eliminated by a minute change in position or heading of an antenna.

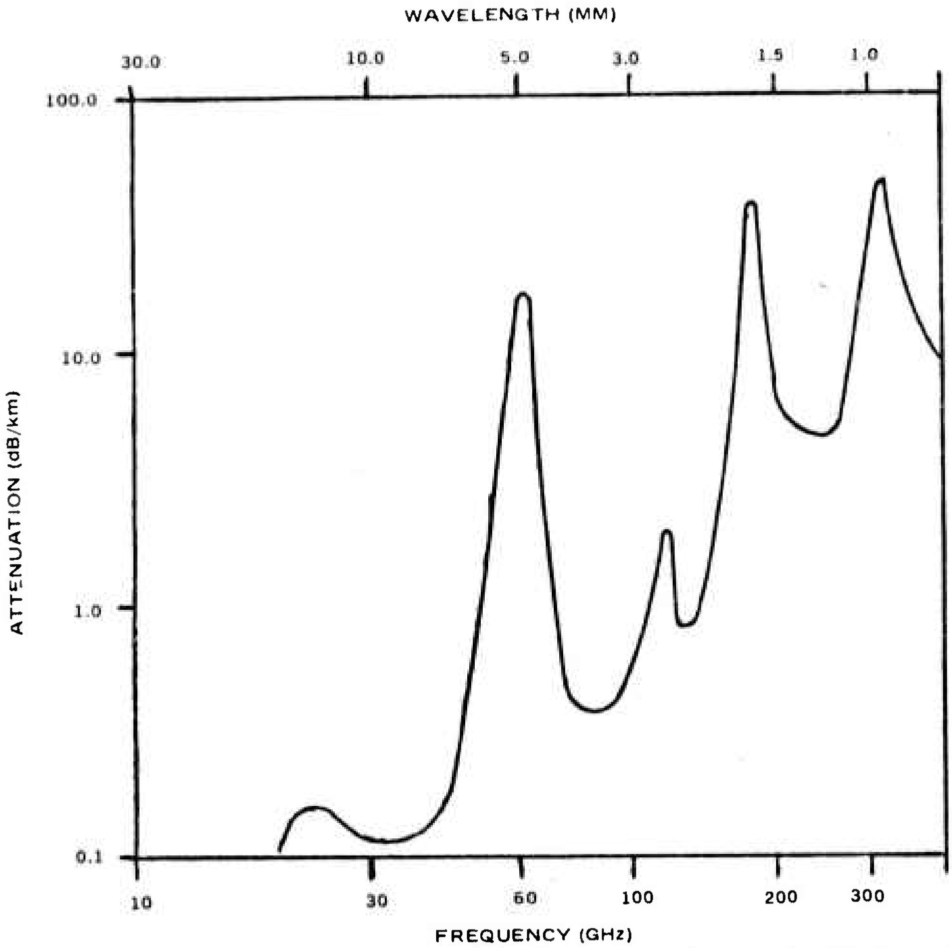


Figure 5. Sea Level Atmospheric Attenuation at MM-Wavelengths (1962 US Standard Atmosphere)

Another important factor is the large coupling and propagation losses that occur on cables at millimeter wave frequencies. This characteristic was demonstrated during the experimental program. A major cause of interference problems in lower frequency systems is that of cable coupling and propagation of interfering signals into various components of the receivers and transmitters. A factor which is not a consideration in this particular study but which pertains to millimeter wave systems separated by greater distances is the relatively large atmospheric propagation losses occurring at millimeter wave frequencies. Since this study was limited to a range of 10 to 100 meters atmospheric propagation losses were negligible.

1. Receiver Susceptibility

A major source of interference problems in millimeter wave systems is that of receiver susceptibility due to intermodulation products and poor rejection of undesired signals.

Typical test setup for evaluating millimeter wave receiver susceptibility characteristics such as intermodulation and rejection of undesired signals is

shown in Figure 6. The millimeter wave sources consisted of IMPATT diode devices. Third order intermodulation products were predicted as follows:

$$2f_2 - f_1, \; 2f_1 - f_2$$

where

f_1 = source No. 1 frequency

f_2 = source No. 2 frequency

A medium quality millimeter wave detector was evaluated during the second quarter experimental effort. This detector had a tangential sensitivity of -48 dBm. The intermodulation products were found to be 50 dB below the fundamental response.

A 60 GHz transceiver system was employed in susceptibility tests performed during the second and third quarter. A block diagram of this transceiver is shown in Figure 7. This transceiver met MIL-STD-461A requirements of CS03, CS04 and CS05 extended to millimeter wave frequencies. It is recommended that test requirements be limited to 60 dB above the minimum discernible signal for the basic millimeter wave receiver. This study reveals that most millimeter wave receiver front ends will begin to overload at this value. When system EMC predictions indicate that specific conditions warrant higher susceptibility test levels it will be necessary to install waveguide filters at the antenna input of the receiver.

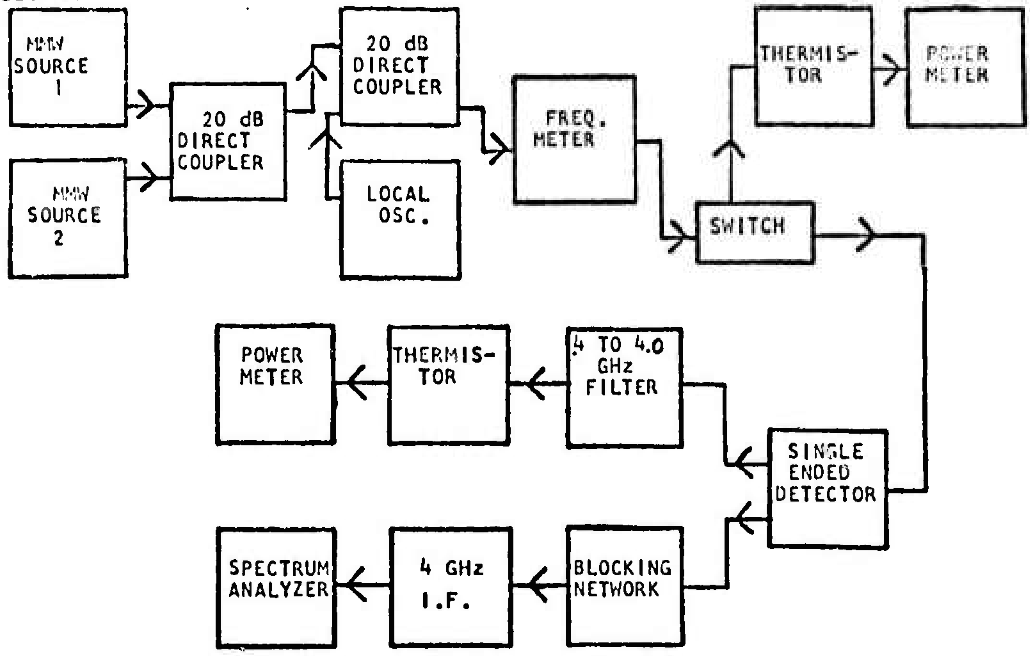


Figure 6. Test Set-up for Intermodulation and Rejection of Undesired Signals

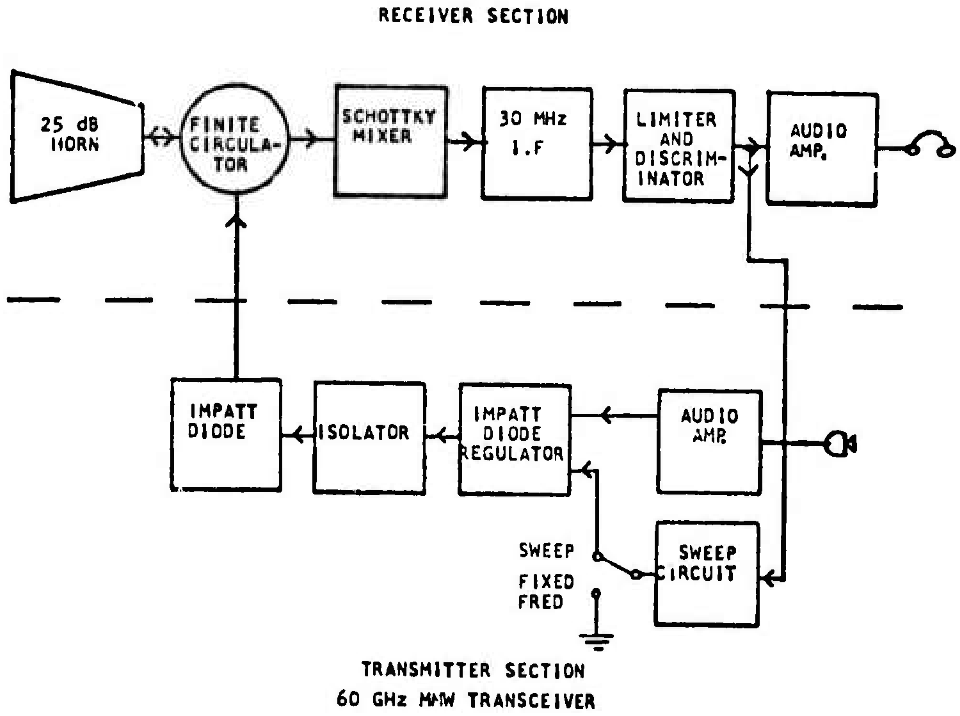


Figure 7. Sixty GHz Transceiver Block Diagram

III. ANALYSIS OF MILLIMETER WAVE SYSTEMS STUDIED DURING LITERATURE SEARCH

Analysis performed during the millimeter wave EMC study included the analysis of inter and intra system EMC considerations in millimeter wave systems. A good example of intra-system EMC considerations was incorporated into a prior program performed at Hughes. This program was studied during the literature search of the Millimeter Wave EMC Study.

A. MILLIMETER WAVE EXPERIMENT FOR ATS-F

An extensive intra-system EMC analysis was performed on a former program known as the Millimeter Wave Experiment for ATS-F (listed in reference 1). This program was performed at Hughes Aircraft Company. The primary objective of the ATS-F millimeter wave experiment was to evaluate characteristics of the synchronous satellite to earth propagation channels at 20 and 30 GHz. The data obtained provides information on the usefulness of millimeter wave frequencies for communications and scientific data link applications.

Several transmitting frequencies were involved in this experiment. The experiment was operated in three modes. A continuous wave mode in which the 20 and 30 GHz carriers only were transmitted, a multitone mode in which nine spectral lines spaced 180 MHz apart and centered at 20 and 30 GHz were transmitted and a communication mode in which FM communication signals were received and transmitted at 20.15 and 30.15 GHz. Interference problems were controlled by the use of bandpass filters.

Three antennas were employed in this system: a 20 GHz horn, a 30 GHz horn and a 20/30 GHz parabolic antenna. The horn antennas 3 dB beamwidths were approximately 6 degrees. The parabolic antenna had a 3 dB beamwidth of approximately 2.3 degrees at 20 GHz and approximately 1.6 degrees at 30 GHz.

The system was tested in accordance with modified versions of MIL-STD-461 and 462. Tests were also performed for frequency stability and spectral purity characteristics which were very important in controlling interference problems. MIL-STD-462 tests RE02 and RS03 were performed without modification. CE01 and CE03 were modified to meet intra-system design requirements. The equipment was designed to meet a 10 millivolt peak to peak level on a powerline. This is a total noise requirement and is not related to levels at specific frequencies as are CE01 and CE03 requirements. CS01 and CS02 were modified. These modified tests consisted of evaluating powerline conducted susceptibility to 40 millivolt peak to peak voltages. Transient tests of CS06 were modified to ±2 volt transients. This system was designed for incorporation into the ATS-F spacecraft and the equipment was not designed to withstand the high level transients of test method CS06. CE06 did not apply since the frequency was above 1.2 GHz. RE03 requirements were analytically demonstrated by providing analyses of the waveguide and filter bandpass characteristics.

B. ANTENNA OUT-OF-BAND CHARACTERISTICS

Introduction

The response of a waveguide radiator to harmonic frequencies cannot be simply specified. The difficulty is that waveguides can and do propagate more than one transmission line mode or field distribution. These modes radiate in different patterns and the total radiation pattern is the sum of the radiation fields of the individual modes weighted by the amplitude and phase of excitation of the modes. This section will describe the various modes and other factors which affect the total antenna field.

The simplest case to consider is the rectangular waveguide. The radiation patterns of any mode can be simply specified in terms of translated sin (x)/x beams. This case will be analyzed and an approximation procedure developed.

1. Modes in Rectangular Waveguide

The modes in rectangular waveguide can be specified as either TE_{mn} or TM_{mn}. Ramo and Whinnery (Reference 8) give the fields for these modes. The most important field component is E_y:

TE	TM
$E_y^{nm} = C_1 \sin \frac{n\pi x}{a} \cos \frac{m\pi y}{b}$	$E_y^{nm} = C_2 \sin \frac{n\pi x}{a} \cos \frac{m\pi y}{b}$

TE waves can exist with either n or m equal to zero, but not both. TM waves can propagate only when both n and m are not equal to zero. The lowest propagating mode is the TE_{10} mode

$$E_y = C_1 \sin \frac{\pi x}{a}$$

with a cutoff wavelength $\lambda_c^{10} = 2a$. (See Figure 8)

For both TE_{mn} and TM_{mn} modes, the cutoff wavelength λ_c^{mn} is given by:

$$\lambda_c^{mn} = \frac{2a\,b}{\sqrt{(mb)^2 + (na)^2}}$$

2. The Excitation of Higher Order Modes

The higher order modes are generated by a source current or by changes in waveguide cross-section. Let us consider a filament of current as shown in Figure 9.

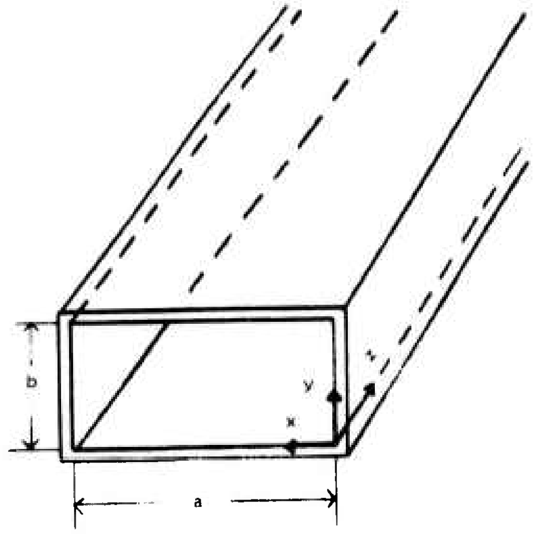


Figure 8. Dimensions for Rectangular Guide.

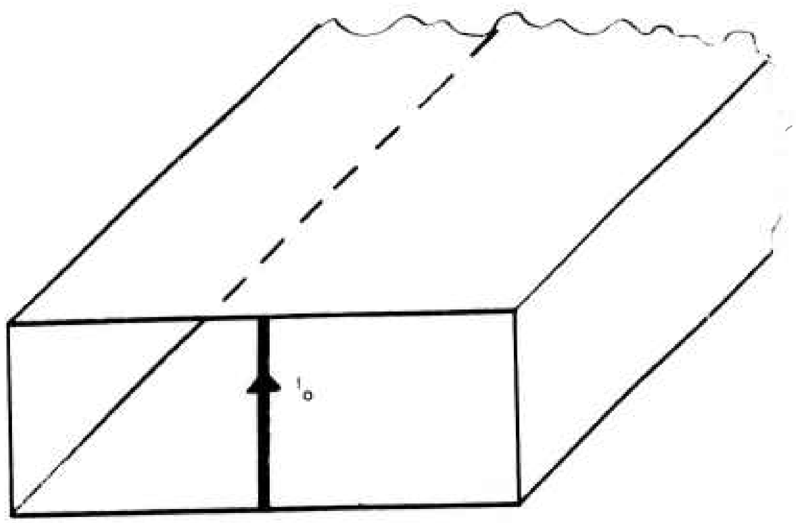


Figure 9. Filamentary Current to Excite TE_{no} Modes in Rectangular Waveguide.

This current can represent either the current in an IMPATT diode source or the current flowing in the mixer. It can be shown that this current excites all of the odd order TE_{no} modes with amplitude A_n:

$$A_n = \begin{cases} 0 & n \text{ even} \\ (-1)^{\frac{n-1}{2}} & n \text{ odd} \end{cases}$$

Thus, an IMPATT diode or a mixer will couple equal power to all of the propagating TE_{no} modes.

The IMPATT diode and the mixer are not directly coupled to free space, but as shown in Figure 10, they pass through either step transitions, linear tapers, and in the case of the IMPATT diode, a circulator. The devices will transform the energy into other modes with different amplitudes and phases.

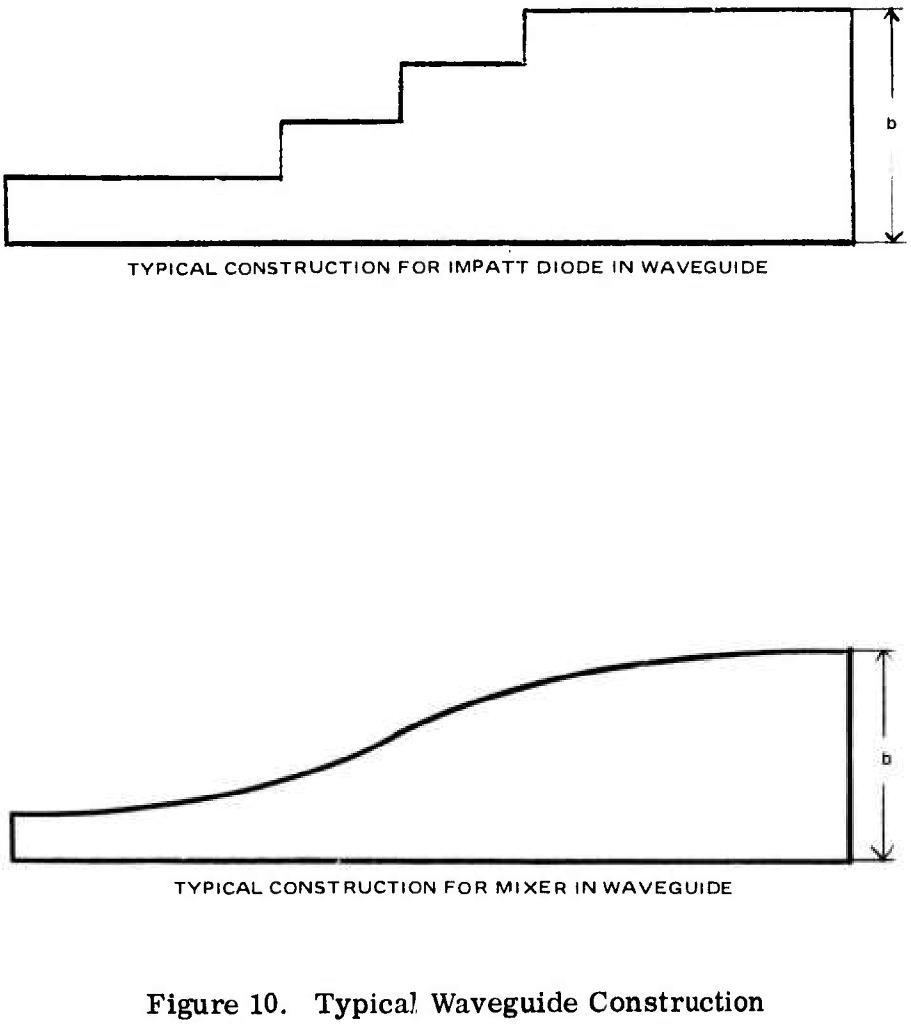


Figure 10. Typical Waveguide Construction

Since these mode conversion processes are difficult to determine, the specification of the fields at the aperture becomes impossible to satisfy. We therefore assume that all of the propagating modes with n odd and m even or odd can and will be excited. The n even modes are antisymmetrical across the a-dimension and will not be excited in a symmetric structure.

3. Radiation Patterns of Higher Order Modes

The radiation patterns for the higher order modes in rectangular waveguides are calculated in Silver, pages 341 to 347 (reference 9). They are repeated in Table 2. The formulas can be interpreted as follows: The two components E_θ and E_ϕ specify the variation in polarization. The peak gain is $4\pi A/\lambda^2$. The expression ψ^2_{mn} is the power pattern.

TABLE 2. SUMMARY OF RADIATION PATTERNS FOR RECTANGULAR WAVEGUIDE MODES

TE-modes.

The electric-field components of the radiation field are

$$E_\theta = -\left(\frac{\mu}{\epsilon}\right)^{1/2} \frac{(\pi ab)^2 \sin\theta}{2\lambda^3 R k_{mn}^2} \left[1 + \frac{\beta_{mn}}{k}\cos\theta + \Gamma\left(1 - \frac{\beta_{mn}}{k}\cos\theta\right)\right] \left[\left(\frac{m\pi}{a}\sin\phi\right)^2 - \left(\frac{n\pi}{b}\cos\phi\right)^2\right] \Psi_{mn}(\theta,\phi)$$

$$E_\phi = -\left(\frac{\mu}{\epsilon}\right)^{1/2} \frac{(\pi ab)^2 \sin\theta \sin\phi \cos\phi}{2\lambda^3 R} \left[\cos\theta + \frac{\beta_{mn}}{k} + \Gamma\left(\cos\theta - \frac{\beta_{mn}}{k}\right)\right] \Psi_{mn}(\theta,\phi),$$

$$\Psi_{mn}(\theta,\phi) = \left[\frac{\sin\left(\frac{\pi a}{\lambda}\sin\theta\cos\phi + \frac{m\pi}{2}\right)}{\left(\frac{\pi a}{\lambda}\sin\theta\cos\phi\right)^2 - \left(\frac{m\pi}{2}\right)^2}\right] \left[\frac{\sin\left(\frac{\pi b}{\lambda}\sin\theta\sin\phi + \frac{n\pi}{2}\right)}{\left(\frac{\pi b}{\lambda}\sin\theta\sin\phi\right)^2 - \left(\frac{n\pi}{2}\right)^2}\right] e^{-j\left[kR - \frac{\pi}{\lambda}\sin\theta(a\cos\phi + b\sin\phi) - (m+n+1)\frac{\pi}{2}\right]}.$$

TM-modes.

$$E_\theta = \frac{mn\beta_{mn}\pi^3 ab}{4\lambda^2 R k_{mn}^2}\sin\theta\left[1 + \frac{k}{\beta_{mn}}\cos\theta + \Gamma\left(1 - \frac{k}{\beta_{mn}}\cos\theta\right)\right]\Psi_{mn}(\theta,\phi),$$

$$E_\phi = 0.$$

$$K_{mn} = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$$

$$\beta_{mn} = \frac{2\pi f}{c}\sqrt{1 - \left(\frac{m\lambda}{2a}\right)^2 - \left(\frac{n\lambda}{2b}\right)^2}$$

The function ψ^2_{mn} can also be easily interpreted. Each factor in ψ_{mn} is a pair of sin x/x beams translated by $\pm m\,\pi/2$. Figure 11 shows the pattern of a TE_{30} mode. As this figure shows, there are two beams translated by $3\pi/2$ in the argument ($\pi a/\lambda\ \sin\theta$).

The fact that each mode causes scanned sin x/x beams lets us use a very simple approximate rule of thumb:

> Let a waveguide propagate modes with indices less than $\hat{m}$. Then, the full gain of the aperture will be realized at several points within a cone of angles with a half angle θ_o
>
> $$\theta_o = \sin^{-1}\left(\frac{\hat{m}}{2b}\right)$$
>
> The gain will fall as $(\sin x/x)^2$ beyond this sector. In a typical situation this angle will be less than two 3dB beamwidths.

This rule of thumb allows us to specify the sector over which higher order modes could radiate with high efficiency.

4. The Effect of Horn Flare Angle

The calculation of radiation gain has been made assuming no phase error. However, a typical horn is flared in both planes creating a pyramidal horn. Such a horn has roughly the aperture distribution of a waveguide of the same size, but with a circular phase front whose center is the point of convergence of the walls. As shown in Figure 12, this phase front leads to a quadratic phase error in the aperture:

$$\phi(x) = \frac{180^\circ\ a^2}{L\lambda}\left(\frac{x}{a}\right)^2 \quad -a \le x \le a$$

The departure of the pattern from the previous case depends only on the maximum phase error $180^\circ\ a^2/L\lambda$. Figure 13 shows the radiation pattern of a twenty wavelength aperture with uniform illumination (sin x/x) pattern as a function of quadratic phase error. This is the E-plane pattern of the TE_{10} mode. Figure 13 shows the pattern of the E-plane of a TE_{10} mode aperture vs. phase error. This data is tabulated in Table 3. Figure 14 shows the pattern of the H-plane of a TE_{10} mode aperture vs. phase error.

In applying these results to the multimode problem, one should use Figure 13 to calculate gain loss of sin x/x beams. The cutoff wavelength should be computed on the basis of the waveguide dimensions at the mouth of the aperture.

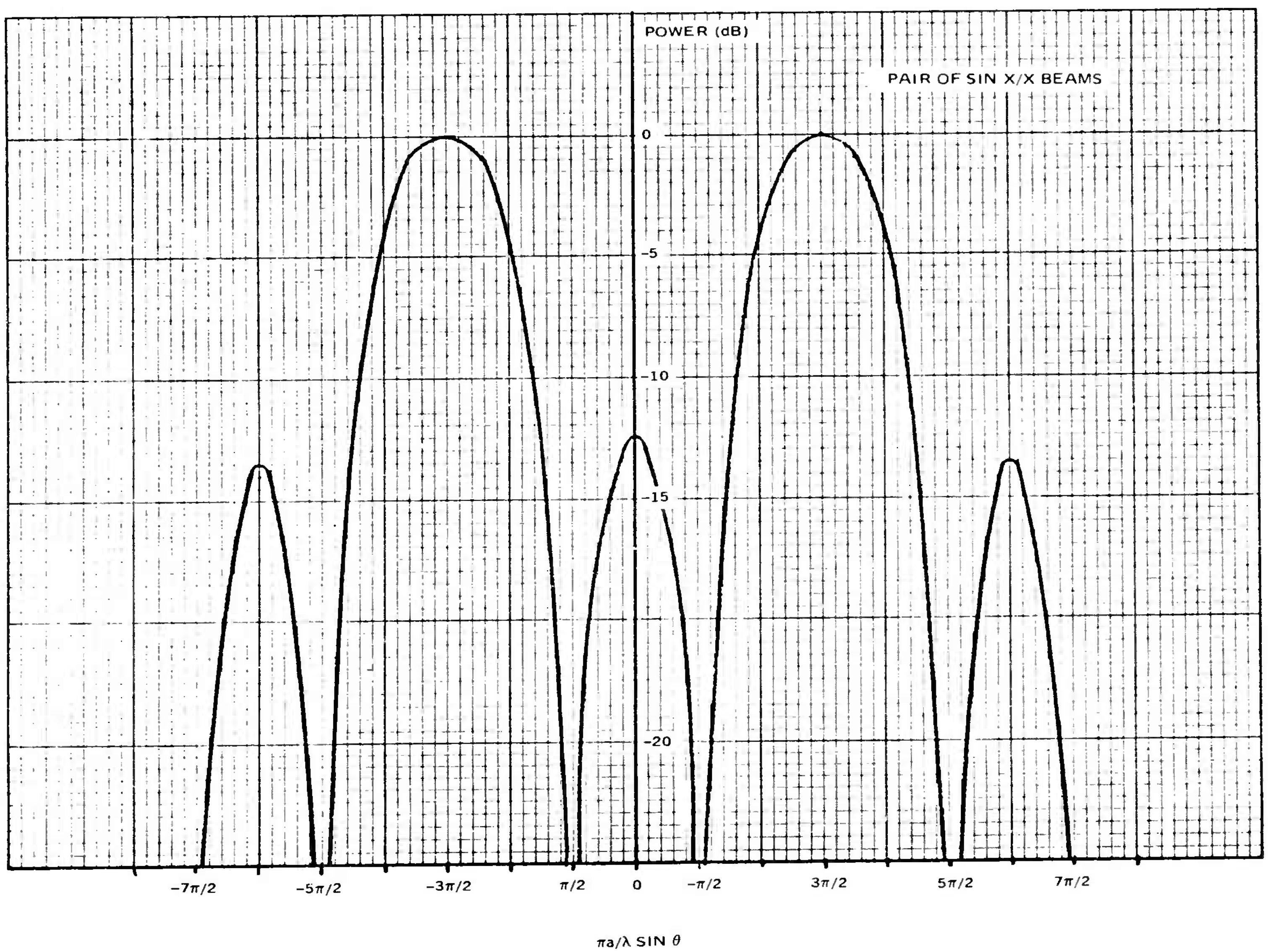
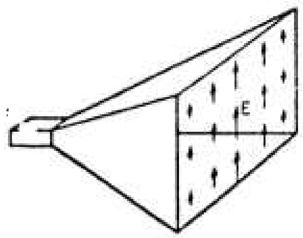
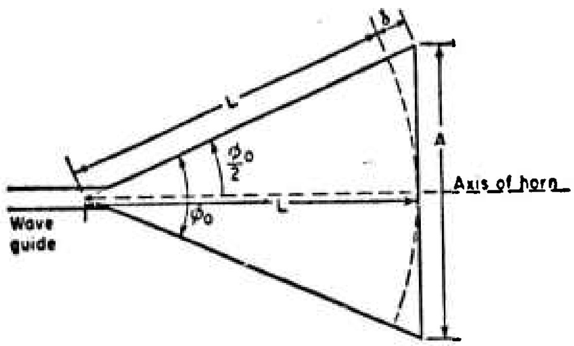


Figure 11. Radiation Pattern of TE30 Mode.



Pyramidal Horn



$$L + \delta = \sqrt{L^2 + \left(\frac{A}{2}\right)^2}$$

$$\delta \approx \frac{A^2}{8L}$$

Figure 12. Calculation of Quadratic Phase Error

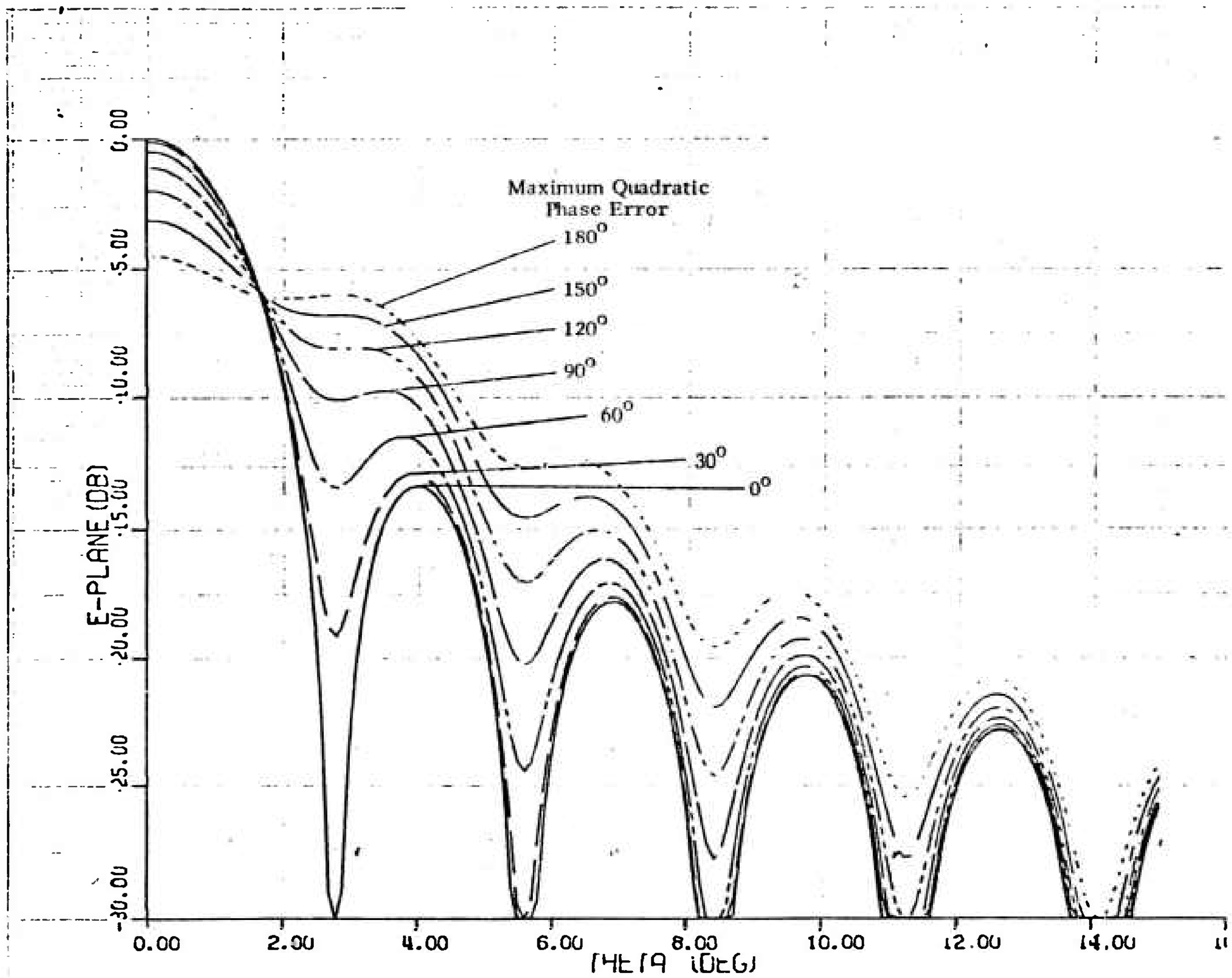


Figure 13. Effect of Quadratic Phase Error on E-plane Radiation Pattern of a Twenty Wavelength Aperture.

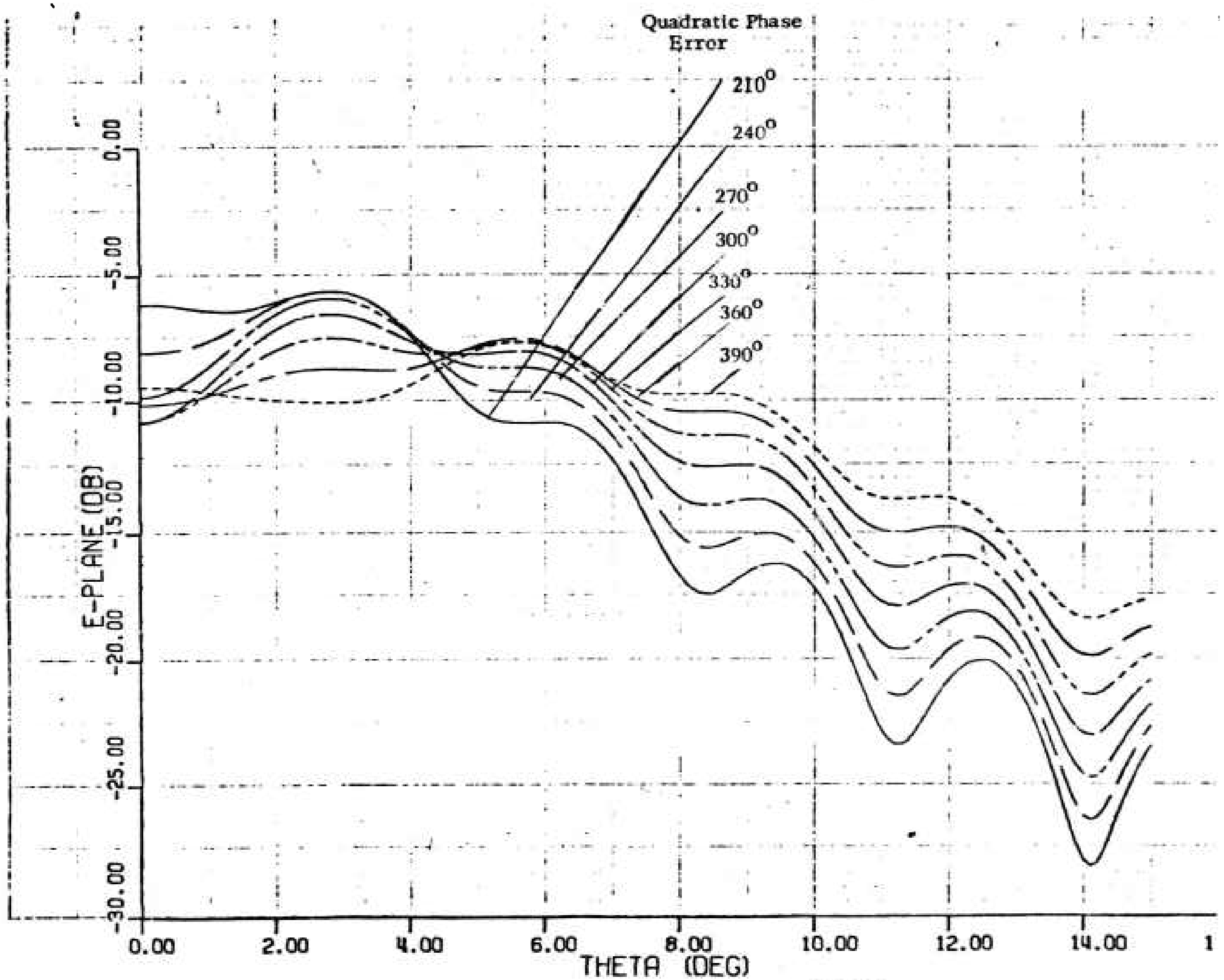


Figure 13. Effect of Quadratic Phase Error on E-plane Radiation Pattern of a Twenty Wavelength Aperture (Continued).

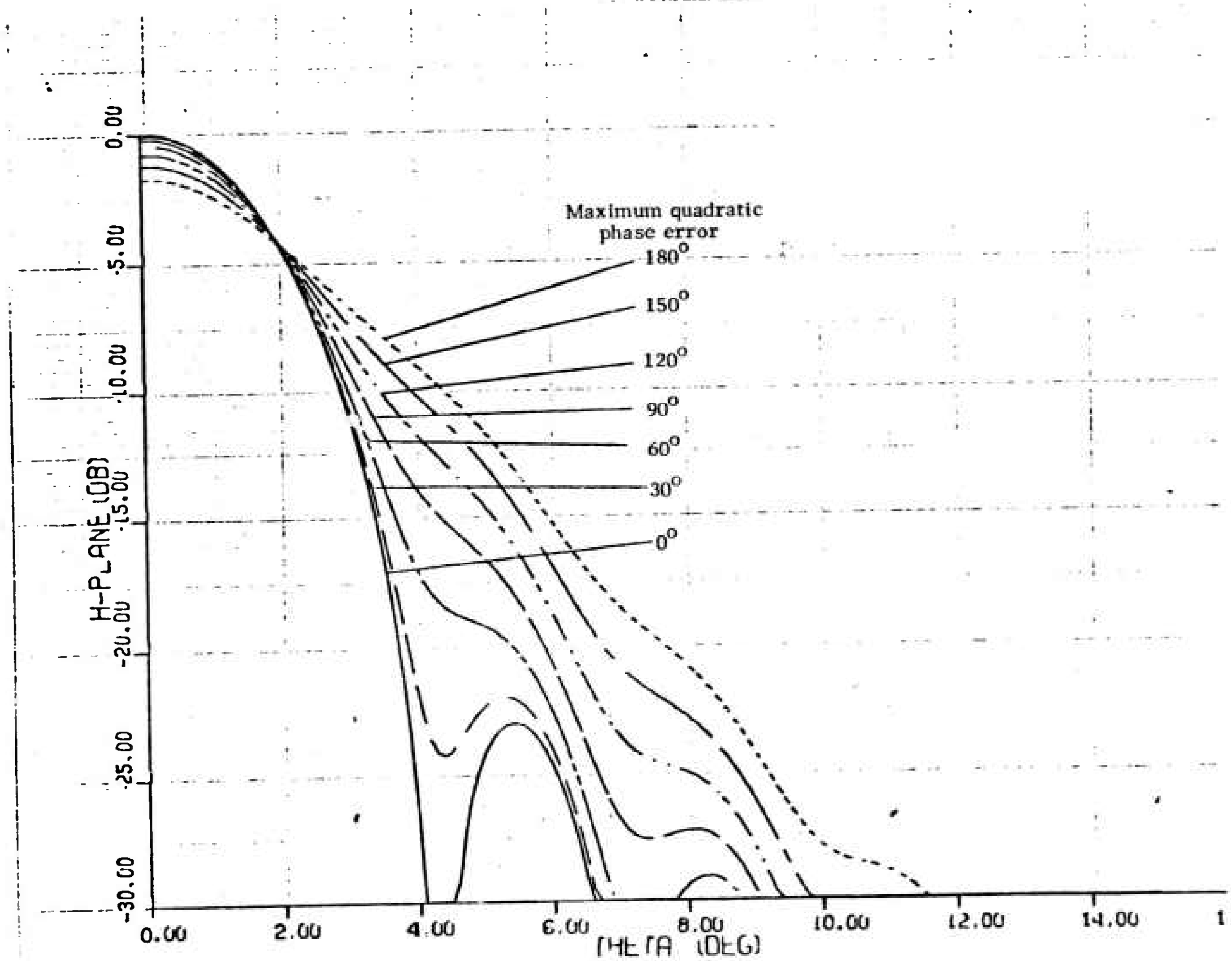


Figure 14. Effect of Quadratic Phase Error on H-plane Radiation Pattern of a Twenty Wavelength Aperture.

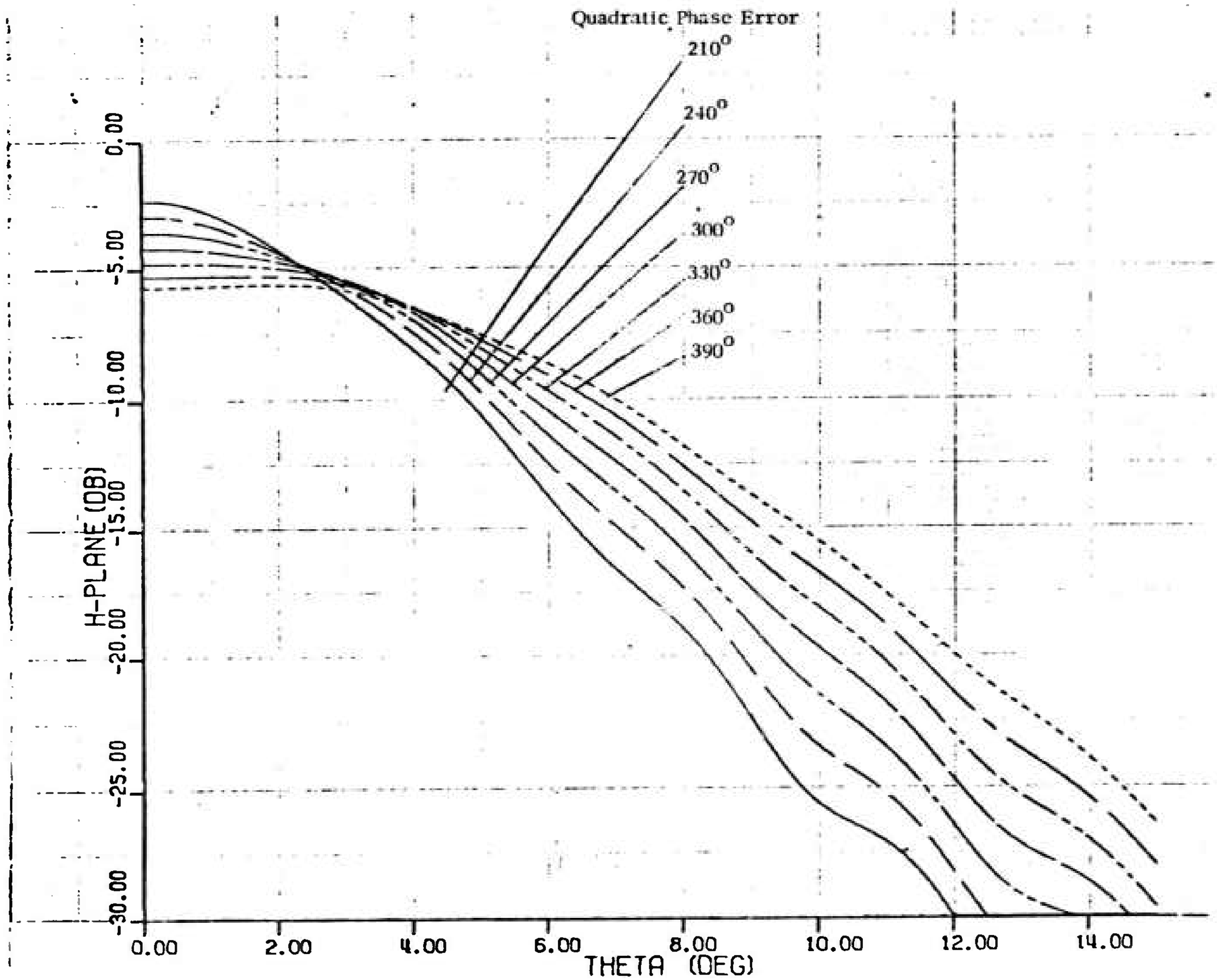


Figure 14. Effect of Quadratic Phase Error on H-plane Radiation Pattern of a Twenty Wavelength Aperture (Continued).

TABLE 3. GAIN LOSS BEAMWIDTH AND SIDELOBE LOSS FOR RECTANGULAR HORN

	E-PLANE				H-PLANE			
Quadratic Phase Error (deg.)	Relative Gain (dB)	BW (deg.)	1st SLL (dB)	2nd SLL (dB)	Relative Gain (dB)	BW (deg.)	1st SLL (dB)	2nd SLL (dB)
0	0	2.5	13.2	17.8	0	3.4	23.0	30.5
15	-0.03	2.5	13.2	17.7	.013	3.4	22.6	30.1
30	-0.12	2.5	12.6	17.5	.050	3.4	21.8	30.0
45	-0.26	2.5	11.9	17.1	.113	3.5	20.4	29.4
60	0.47	2.5	11.0	16.6	.201	3.6	Swallowed in main beam	28.6
75	0.74	2.6	9.88	15.9	.314	3.8		Swallowed in main beam
90	-1.07	2.6	8.7	15.1	.451	3.9		
105	-1.46	2.7	7.45	14.2	.611	4.1		
120	-1.92	2.8	6.2	13.1	.794	4.5		
135	-2.45	3.0	Swallowed in main beam	12.0	1.000	4.8		
150	-3.05	3.4		Swallowed in main beam	1.226	5.2		

Example Calculation

As an application of the above theory, a 30 GHz pyramidal rectangular horn will be examined. The dimensions of the aperture are

$$\begin{aligned} L &= 7.50 \text{ inches} \\ H &= 2.76 \text{ inches} \\ W &= 3.24 \text{ inches} \\ \lambda &= 0.3934 \text{ inch} \end{aligned}$$

The E-plane quadratic phase error is

$$\phi_M = \frac{360°}{\lambda} \left[\sqrt{L^2 + \left(\frac{H}{2}\right)^2} - L \right]$$

$$= 360° \left(\frac{0.1259}{0.3934}\right) = 115°$$

The H-plane quadratic phase error is

$$\phi_M = \frac{360°}{\lambda} \left[\sqrt{L^2 + \left(\frac{W}{2}\right)^2} - L \right]$$

$$= 360° \left[\frac{0.1729}{0.3934}\right] = 158°$$

The gain for the TE_{10} mode is calculated from Table 4 using Figures 13 and 14 and Table 3.

TABLE 4. SAMPLE CALCULATION FOR A 30 GHz PYRAMIDAL RETANGULAR HORN

$\frac{4\pi A}{\lambda^2}$		+28.60 dB
Cosine Aperture Distribution (80% efficiency)		-1.0 dB
E-plane phase error		-1.74 dB
H-plane phase error		-1.34 dB
Net Gain		24.52 dB
Sidelobe Level	1st	2nd
E-plane	6.0 dB	13.0 dB
H-plane	--	--

The quadratic phase error at 60 and 90 GHz is double and triple the values at 30 GHz respectively. The factor $4\pi A/\lambda^2$ is four and nine times larger respectively. The cosine aperture distribution takes into account the antenna performance departure from the ideal antenna performance. This value is a constant minus 1 dB for 80 percent efficiency at all frequencies.

Table 5 gives the calculation of the gain at 60 and 90 GHz respectively.

TABLE 5. ANTENNA GAIN FOR A 30 GHz PYRAMIDAL HORN USED AT 60 AND 90 GHz

	60 GHz	90 GHz
$\frac{4\pi A}{\lambda^2}$	34.60 dB	38.15 dB
Cosine Taper	-1.00 dB	-1.00
E-plane loss	-6.5 (230° phase error)	-10.00 dB (345° phase error)
H-plane loss	-4.6 dB (316° phase error)	-6.5 dB (474° phase error)
Net Gain	22.5 dB	20.65 dB

The gain loss at 90 GHz in the H-plane cannot be determined from Figure 14. because the phase error exceeds 360 degrees. An asymptotic formula for very large phase error was used and found to be

$$\text{E plane loss} \sim 10 \log_{10} \left(\frac{45^\circ}{\phi_m}\right)$$

$$\text{H plane loss} \sim 10 \log_{10} \left(\frac{112}{\phi_m}\right)$$

These formulas are shown on Figure 15 along with the exact calculations out to ϕ_n equal to 360 degrees.

Concerning extrapolating these results to other aperture sizes, all of the calculated patterns are based on a twenty wavelength aperture. The beam shapes for any other size aperture are equal to the plots shown in Figures 13 and 14 except that the angle theta on the horizontal axis must be scaled by the factor $20/(L/\lambda)$.

5. Conclusion

The radiation patterns for both fundamental and harmonic radiation from multimode rectangular waveguides has been considered. In the case of the rectangular horn it has been shown that the full gain of the aperture can be realized within a cone of angles less than two beamwidths on either side of boresight. The effects of aperture flare angle have been considered for rectangular horns, and both rigorous loss values for small errors and asymptotic forms for large errors have been determined.

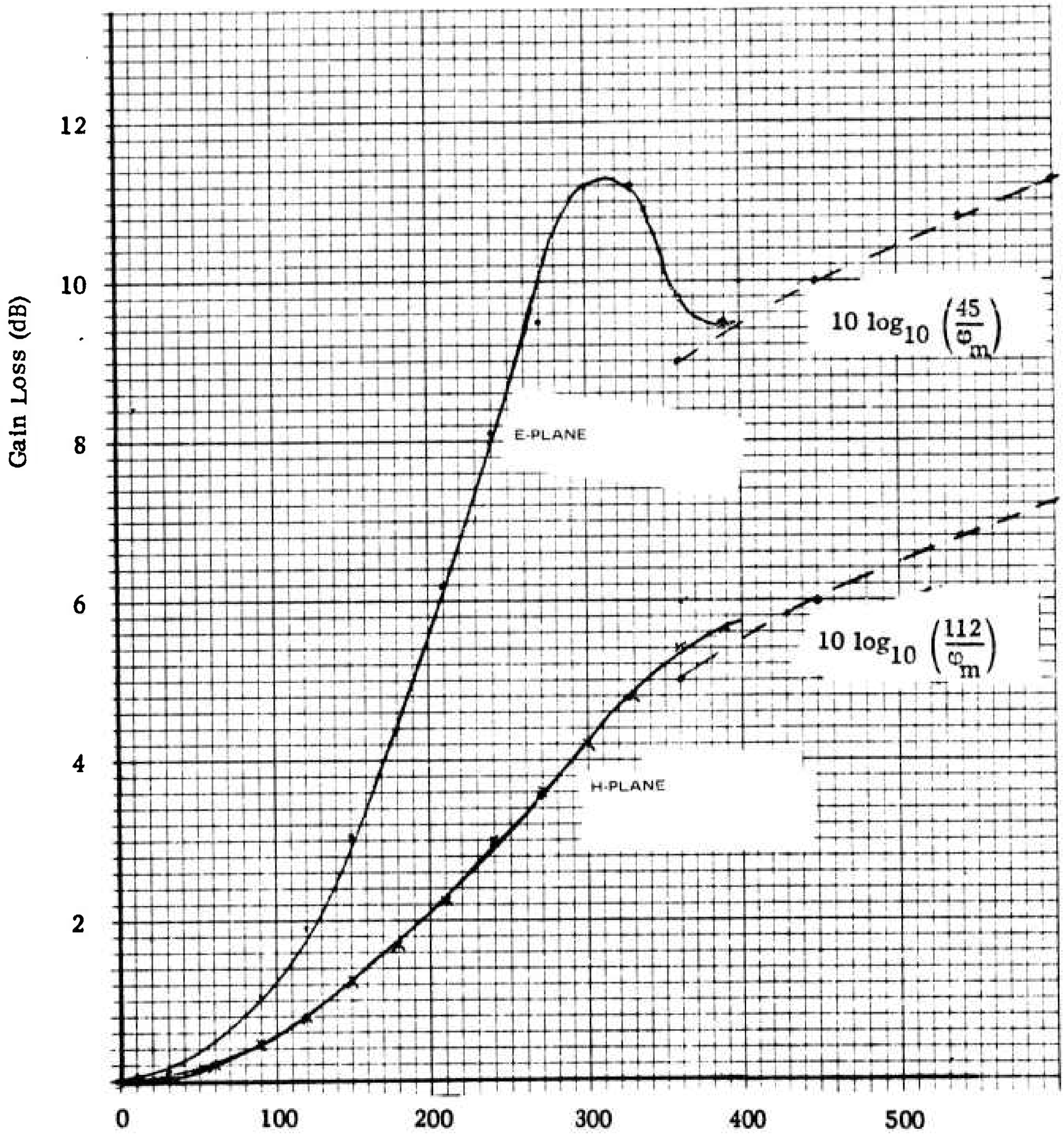


Figure 15. Quadratic Phase Error φ (deg.)

C. SURVEY OF MILLIMETER WAVE FILTER STATE-OF-THE-ART

The characteristics of millimeter wave filters can, in general, be expected to be the same as microwave (4-18 GHz) filters, but because of the more difficult technological problems that are encountered in the fabrication of millimeter wave circuits, the current state-of-the-art is represented by only the simplest types. All millimeter wave filters are made with distributed circuit elements that are coupled together to achieve a particular pass and/or rejection characteristic. To date most filters have been made in waveguide, but stripline and microstrip circuits are being developed at frequencies as high as 200 GHz (reference 6). Because of the distributed nature of the networks involved, the millimeter wave filters generally have multiple response bands which can be harmonically related to the fundamental response when they are due to the periodic nature of the circuits and which can occur at random frequencies when they are due to the generation of unwanted modes in the circuits. This latter type of spurious response can often be suppressed by special construction techniques that are used at microwave frequencies but have not yet been accomplished at millimeter wave frequencies. However, most millimeter wave circuits have not been characterized over sufficiently broad bands to identify the exact position or strength of these spurious responses so that nothing quantitative can be said about them.

Most of the work in millimeter waves has been in Ka - band (26.5 - 40 GHz) where most of the instrumentation that is available at lower frequencies has been implemented (e.g., noise sources, network analyzers). The activity decreases as the frequency increases, disappearing in the 100-200 GHz region. In the following discussion we will outline the results of our filter work at 94 GHz and summarize the results of other millimeter wave filter work that has been recorded.

1. Low Pass Band Reject Filters

Two types of filters have been developed for use in millimeter wave circuits. The first is a low pass/band reject filter formed from alternating high and low impedance coaxial lines as shown in Figure 16. This type of filter is used to provide diodes that are mounted in waveguides with bias and/or i.f. signals while confining the millimeter waves to the waveguide. The general shape of the filter insertion loss is shown in Figure 17. We note the pass bands at DC and 2 f_o. This response is calculated with the assumption that there are only TEM waves propagating on the coaxial lines. For typical filter dimensions it is often difficult to maintain that condition since the first non-TEM mode propagates when the wavelength becomes much smaller than the diameter of the outer diameter of the coaxial line. When the filter is operating in such a region there are spurious responses that appear superimposed on the characteristic of Figure 17. When operating in the upper portion of the millimeter wave spectrum manufacturing limitations can cause the first spurious response to be only 10-30 percent above the normal operating frequency.

2. Direct Coupled Cavity Bandpass Filter

The other type of millimeter wave filter that has been used at Hughes is the direct coupled cavity bandpass filter (reference 7). With this structure it is possible to fabricate bandpass filters with either Chebyshev or Butterworth

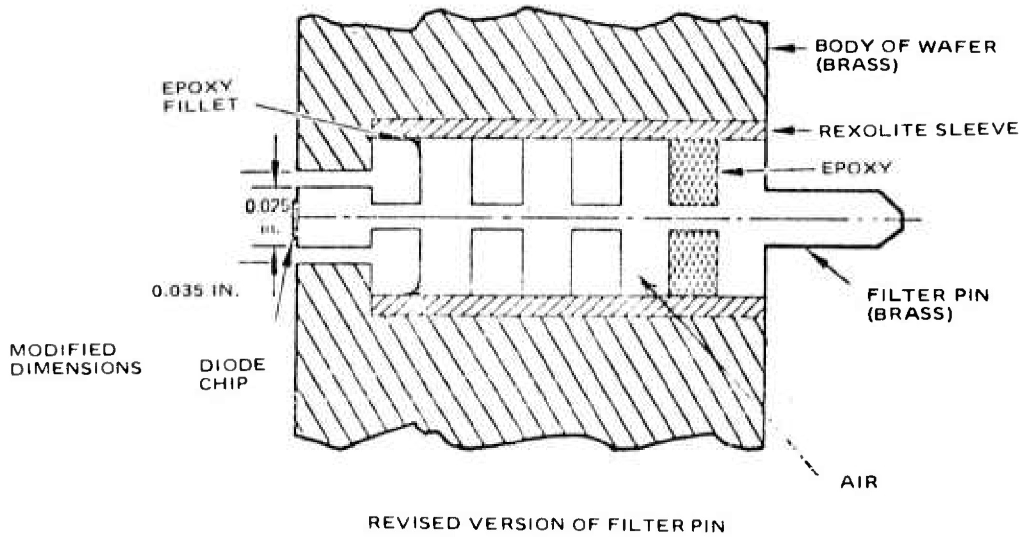


Figure 16. Sketch of the Stepped Impedance, Low Pass Filter Assembly

response in the passband. These filters are usually designed by transforming the design for a similar low pass filter. The exact characteristics will depend on the particular type of cavity and coupling that is used, but because of the increase in the density of allowable modes in a structure as the frequency increases it is difficult to predict the exact filter behavior over large frequency variations. In general, filters have not been characterized in a range that is greater than a standard waveguide band. Most of the filters constructed at Hughes have used one of two different cavity types: 1) a rectangular cavity operating in the TE_{101} mode and 2) a cylindrical cavity operating in the TE_{011} mode. The cylindrical cavity has higher Q (> 10,000 at 60 GHz) thus allowing the construction of small fractional bandwidth low loss filters. However, it has more spurious responses close to the operating band, so the rectangular cavity has been used for larger bandwidth filters. The basic cavity Q is important in filter construction since the excess loss in the passband is given by

$$\Delta L. \simeq 8.69 \frac{C_n}{wQ}$$

where C_n is a constant that relates to the filter response function and w is the fractional bandwidth of the filter. For a three section filter with .1 dB Chebyshev response $C_n \approx 1.6$. The theoretical cavity Q's for the two different types of cavities are

$$Q = \frac{b}{\delta} \frac{1}{1 + \frac{2b}{ac}\left(\frac{a^3 + c^3}{a^2 + c^2}\right)}$$

for the rectangular cavity and

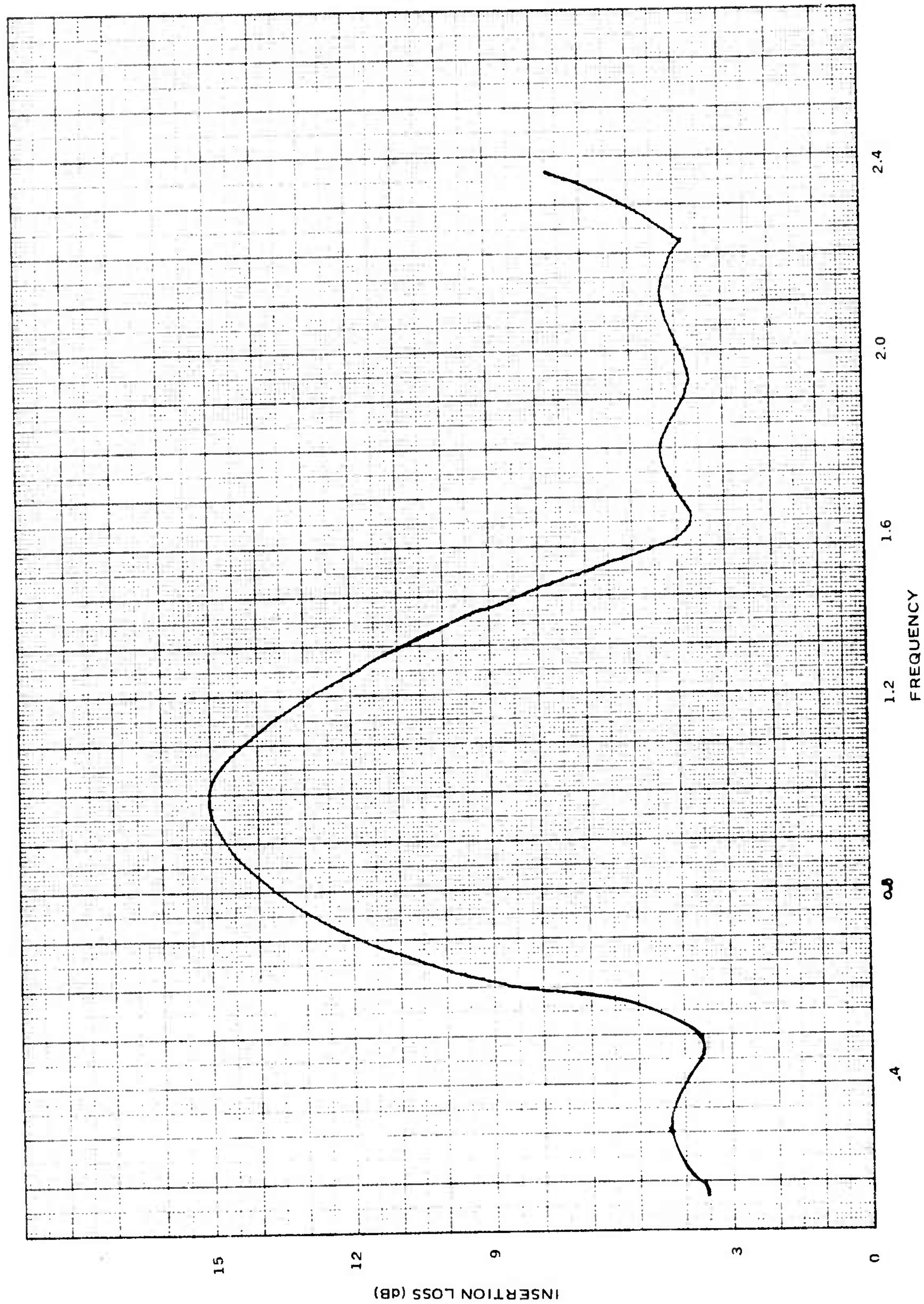


Figure 17. Filter Pin Insertion Loss

$$Q = \frac{D}{\delta} \frac{(3.83)^2 + \frac{\pi^2 D^2}{4L^2}}{(3.83)^2 + \frac{\pi^2 D^3}{4L^3}}$$

for the cylindrical cavity. Here δ is the skin depth of the cavity wall

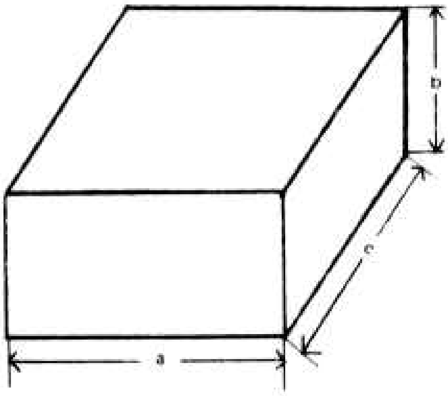
$$\delta = \left(\frac{2}{\mu \Omega \sigma} \right)^{1/2}$$

and is approximately $.2\mu$ for copper at 90 GHz. The other symbols refer to Figure 18. Therefore, typical Q's for the two cavity types at 90 GHz are 9200 for the cylindrical cavity and 2800 for the rectangular cavity. TE_{101} rectangular cavities have been made at 90 GHz with a measured Q of 3100 ±20%. In order to achieve that type of number, great care must be exercised to maintain a high surface finish in the cavity and to keep all surfaces very clean. The result is shown in Figure 18. Cylindrical cavities at 60 GHz have shown Q's in excess of 10,000 which compares with theoretical values of $\geq$ 11,000.

As mentioned above the rejection bands of millimeter wave filters are usually not characterized completely. This situation is due to lack of sufficiently broadband sources and to insufficient dynamic range in the measuring equipment. Generally, insertion loss measurements are limited to ~ 30 dB. A typical filter response is shown in Figure 19. The measured insertion loss agrees well with that predicted by the design theory.

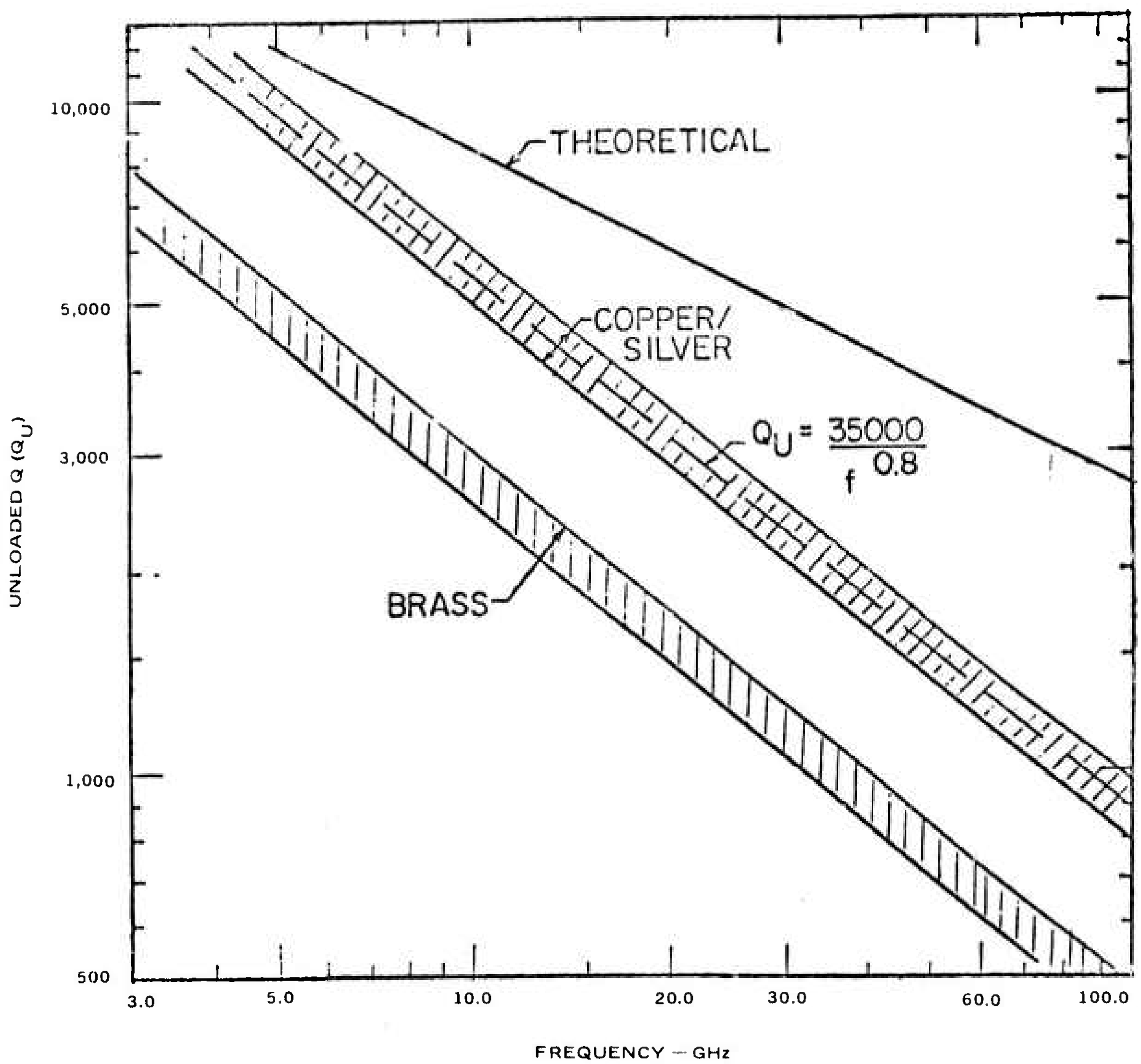
3. Summary

Summarizing the state-of-the-art in millimeter wave filters, indicates that direct coupled cavity filters with near theoretical response can be fabricated over the 30-100 GHz band. Experimental investigations have been limited to bandwidths $\leq$ 2%, but it is reasonable to expect that the type of performance demonstrated in the same type of waveguide filter at X-band is scalable to millimeter wave frequencies.



$$\lambda_o = \frac{2}{\sqrt{(l/a)^2 + (m/b)^2 + (n/c)^2}}$$

(a) Dimensions



(b) Q Characteristics

Figure 18. Rectangular Prism Resonant Cavity

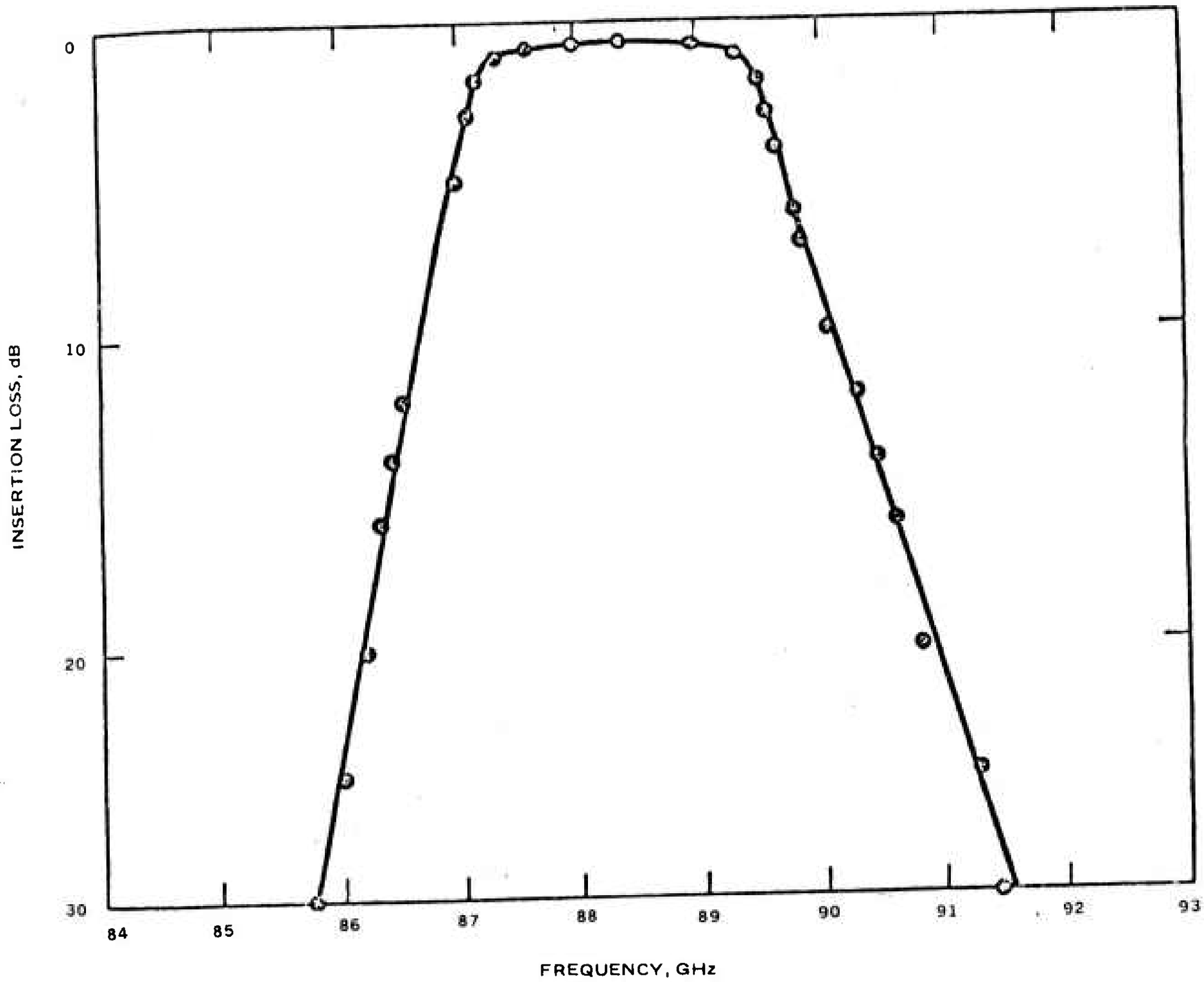


Figure 19. Experimental Filter Response Skirt Rejection

D. EFFECTS OF COLLOCATED MICROWAVE SYSTEMS ON MILLIMETER WAVE SYSTEMS

As part of the evaluation of system interference limits, computer program MSTR2 was employed. The program used typical data obtained from the experimental portion of this contract. The first program run simulated a typical low frequency tropospheric communications system and analyzed its effect on a millimeter wave communication system. (See Figure 20A.) The second run deals with a low frequency radar and millimeter wave communications systems (see Figure 20B). The program simulated typical Army deployments. A familiarity with the MSTR2 program description will be helpful in reading this analysis. Table 6 lists the various equipment specifications.

TABLE 6. EQUIPMENT DESCRIPTION

Low Frequency Communication Transmitter

Center Freq = 5 GHz
Power Output = 1 kW
Antenna Gain = 42.5 dB center beam
12.5 dB 2nd side lobe
Transmitter Spurious Outputs = 10 GHz, 0 dBm; 15 GHz, -8 dBm;
20 GHz, -15 dBm; 25 GHz, -22 dBm;
30 GHz, -30 dBm; 35 GHz, -30 dBm;
40 GHz, -30 dBm; 45 GHz, -30 dBm;
50 GHz, -50 dBm.
Second side lobe considered in analysis

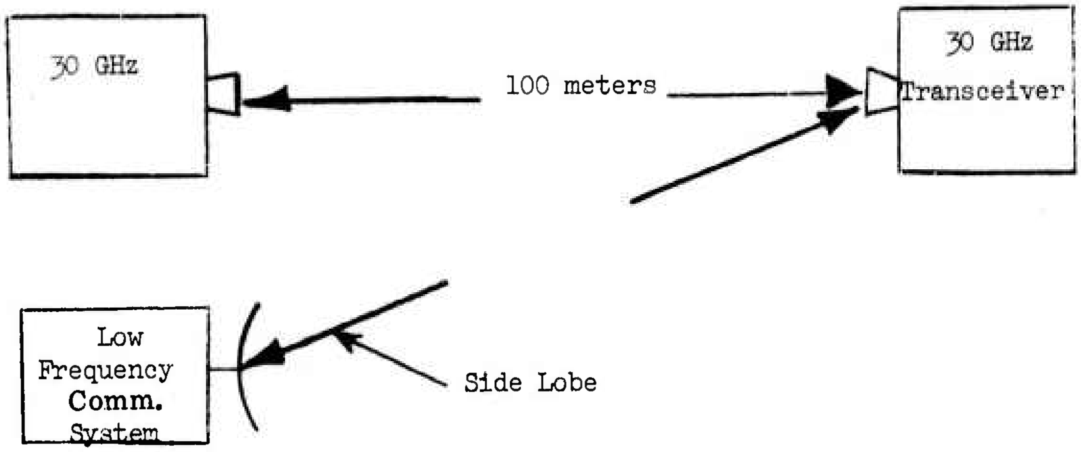
Receiver

Center Freq = 30 GHz
Sensitivity = -90 dBm
3 dB bandwidth = 4 GHz
Bandwidth at 0 dBm sensitivity = 15 GHz
Antenna Gain = 25 dB. Main beam used for analysis

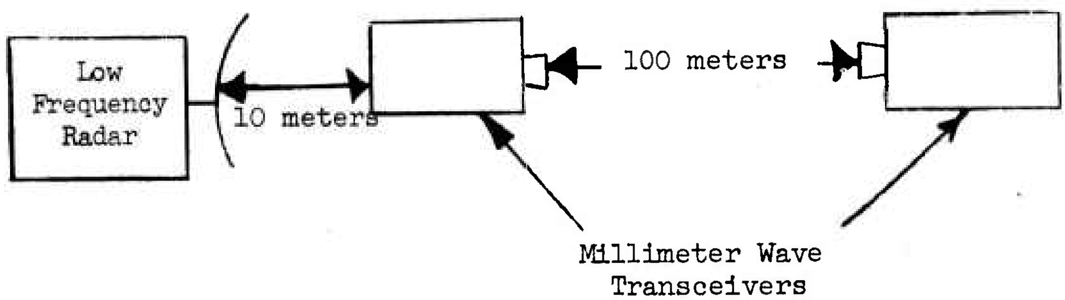
Millimeter Transmitter

Center Freq = 30 GHz
Power Distribution = 200 mW
Power Output = 200 mW
Antenna Gain = 25 dB

MSTR2 accepts one transmitter, one receiver, one receiver antenna, and one transmitter antenna. The two transmitter outputs were combined into one spectrum and the total spectrum described to the computer. The same was done with the two receivers. The combining process is simple as will be seen.



(a) LOW FREQUENCY COMMUNICATION SYSTEM DEPLOYMENT



(b) LOW FREQUENCY RADAR SYSTEM DEPLOYMENT

Figure 20. System Deployments

The low frequency transmitter operates at 1 kW output into a second side lobe antenna gain of 12.5 dB. The millimeter wave transmitter operates at 200 milliwatts into an antenna gain of 25. Because there is a difference of 12.5 dB between the two antennas, 12.5 dB is subtracted from 23 dB (200 mW). This yields 10.5 dB. Because the propagation loss at 110 meters is -52 dB and at 100 meters it is -31 meters, 21 dB is subtracted from the above 10.5 dB to yield -10.5 dB. This new value is listed at the millimeter wave transmitter output at 30 GHz. A similar process yields the total receiver spectrum.

After the program is initiated, the computer asks the user the necessary questions to provide the computer with the needed information. In the course of the program, information will be requested concerning the transmitter fundamental output. Since the computer is programmed to calculate output levels along the skirts for the fundamental output only, the strongest signal is selected as the fundamental output. This signal is the output at 5 GHz. All other signals produced by the two transmitters, whether fundamental or spurious, are treated in the spurious output section of the program. Because the low frequency antenna has the lowest cutoff frequency, it is described as the "transmitter antenna" to the computer. The receiver detects a signal when the "System Response" (see computer output) is positive.

From the above discussion and the following data, it can be seen that a very complex communications deployment can be analyzed for desired responses.

It can also be seen that selective deployment of millimeter wave equipment can avoid potential interference problems. A study of typical Army deployments indicates that the millimeter wave systems will be collocated with lower frequency systems in the 1.0 to 6.0 GHz range. Therefore consideration of any special interference reducing techniques would be necessary only when multiple collocated millimeter wave systems are deployed.

Computer Output

The computer program input information and a portion of the computer program output is listed below. The output has been limited to those frequencies of interest only, i.e. those frequencies where interference occurs, which was at 29, 30 and 31 GHz.

This program evaluates the characteristics of a Receiver-Transmitter-Antenna System for interference of desired operation. The data output is given in terms of the frequency at which interference occurs and the total system response is greater than zero, interferences is probable to occur.

Units for Data:

Frequency – Any units as long as the same units are used throughout the program.
Gain and Response – dB or dBm as appropriate
Distance – Meters

The following information generates data for the Receiver frequency response:

How many frequencies do you want checked for probable interference — maximum = 200? 49

What is the center frequency of the receiver and its sensitivity? 30, -90

What are the upper and lower 3 dB frequencies? 32, 28

What are the frequencies at the bottom of the skirt above and below the center frequency and the receiver sensitivity at those frequencies? 45, 20, 0

What are the upper and lower band limits and the receiver sensitivity at those frequencies? 50, 1, 30

The following information generates data for the Transmitter fundamental output.

What is the center frequency of the transmitter and its output? 5, 60

What are the upper and lower 3 dB frequencies? 6, 4

What are the frequencies at the bottom of the skirt above and below the center frequency and the transmitter output at those frequencies: 8, 2, -40

What is the transmitter output at the band edges? -120

The following information generates data for the propagation losses.

What is the distance between the receiver and transmitter antennas? 110

The following information generates data for the receiver antenna.

What is the gain at the bottom band edge? -70

What is the frequency and gain of the first break point? 5, -50

What is the frequency and gain of the second break point? 29, 25

What is the frequency and gain of the third break point? 30, 24.5

What is the frequency and gain of the fourth break point? 35, 24

What is the gain at the upper band edge? 23

The following information generates data for the transmitter antenna.

What is the frequency and gain of the first break point? 4, 12.5

What is the gain at the bottom band edge? -100

What is the frequency and gain of the second break point? 9, 10.5

What is the frequency and gain of the third break point? 30, 8.5

What is the frequency and gain of the fourth break point? 40, 7.8

What is the gain at the upper band edge? 6

The following information generates data for the RF environment. The data can concern a neighboring transmitter or any other source of RF energy.

How many RF signals are there to consider (maximum = 50)? 9

What is the bandwidth of the RF energy? 2

What is the frequency and amplitude of the first signal? 10, 0

What is the frequency and amplitude of the next signal? 15, -8

What is the frequency and amplitude of the next signal? 20, -15

What is the frequency and amplitude of the next signal? 25, -22

What is the frequency and amplitude of the next signal? 30, -10.5

What is the frequency and amplitude of the next signal? 35, -30

What is the frequency and amplitude of the next signal? 40, -30

What is the frequency and amplitude of the next signal? 45, -30

What is the frequency and amplitude of the last signal? 50, -50

The following data generates receiver secondary response information.

How many secondary responses are there to consider (maximum = 50)? 0

Frequency	System Response
28	-33.34966
29	80.7753
30	81.6801
31	80.0101
32	-38.87419

In order to evaluate a communication system performance in the presence of radar harmonic outputs, program MSTR2 was again run with emphasis placed on the harmonic interference problems in a radar-communications system deployment. This analysis simulates a condition similar to a deployment consisting of millimeter wave systems in the main beam of a 1 kW radar operating at 5 GHz.

The radar harmonic content was obtained from experiments performed during the third quarter. The communication system data is from a Hughes-built transceiver operating at 35 GHz. See Table 7 below for an equipment summary. The transceiver was located in the radar main beam thereby simulating worst-case conditions.

TABLE 7. DESCRIPTION OF EQUIPMENT

Radar

7th Harmonic: Freq = 35 GHz, Amplitude = 33.5 dBm
3 dB Bandwidth = 500 MHz
8th Harmonic: Freq = 40 GHz, Amplitude = 39.5
3 dB Bandwidth = 500 MHz

Receiver

Freq = 35 GHz, Sensititivity = -70 dBm
3 dB Bandwidth = 500 MHz

Antennas

Radar – Parabolic dish, Gain = 29.5 dB @ 35 GHz
Receiver – Horn, Gain = 10 dB @ 35 GHz

The data was supplied to the computer in the same fashion as described for the previous computer run; therefore an explanation will not be repeated here. Examine the program output for further details.

Inspection of the output reveals the receiver will detect the seventh radar harmonic spectrum in the area of 35 GHz. However, the eighth harmonic (40 GHz) is undetected as the receiver sensitivity is not high enough at this frequency.

The results of this computer run indicate higher order harmonics from radars operating in the 1 to 10 GHz region could be a cause of interference to other millimeter wave systems operating in the 10 to 100 GHz region. These potential interference situations can be avoided by careful selection of operating frequencies and equipment deployments.

Computer Output

This program evaluates the characteristics of a receiver-transmitter-antenna system for interference of desired operation. The data output is given in terms of the frequency at which interference occurs and the total system response. When the total system response is greater than zero, interference is probable to occur.

Units for data:

Frequency — any units as long as the same units are used throughout the program

Gain and response — dB or dBm as appropriate

Distance — meters

The following information generates data for the receiver frequency response.

How many frequencies do you want checked for probable interference — maximum = 50? 50

What is the center frequency of the receiver and its sensitivity? 35, -70

What are the upper and lower 3 dB frequencies? 35, 25, 34.75

What are the frequencies at the bottom of the skirt above and below the center frequency and the receiver sensitivity at those frequencies? 40, 30, -20

What are the upper and lower band limits and the receiver sensitivity at those frequencies? 41.25, 28.75, 10

The following information generates data for the transmitter fundamental output.

What is the center frequency of the transmitter and its output? 35, -33.5

What are the upper and lower 3 dB frequencies? 35.25, 34.75

What are the frequencies at the bottom of the skirt above and below the center frequency and the transmitter output at those frequencies? 36.75, 33.25, -93.5

What is the transmitter output at the band edges? -200

The following information generates data for the propagation losses.

What is the distance between the receiver and transmitter antennas? 10

The following information generates data for the receiver antenna.

What is the gain at the bottom band edge? 0

What is the frequency and gain of the first break point? 32, 7

What is the frequency and gain of the second break point? 35, 10

What is the frequency and gain of the third break point? 37, 9.6

What is the frequency and gain of the fourth break point? 39, 9.3

What is the gain at the upper band edge? 9.0

The following information generates data for the transmitter antenna.

What is the gain at the bottom band edge? 28.9

What is the frequency and gain of the first break point? 32, 28.7

What is the frequency and gain of the second break point? 35, 28.5

What is the frequency and gain of the third break point? 37, 28.4

What is the frequency and gain of the fourth break point? 39, 28.3

What is the gain at the upper band edge? 28.2

The following information generates data for the RF environment. The data can concern a neighboring transmitter or any other source of RF energy.

How many RF signals are there to consider (max = 50)? 1

What is the bandwidth of the RF energy? 0.5

What is the frequency and amplitude of the first signal? 40, -39.5

The following data generates receiver secondary response information.

How many secondary responses are there to consider (max = 50)? 0

Frequency	System Response
34.5	37.77459
34.75	44.0793
35	37.94543
39.5	-88.53358
39.75	-10.55171
40	-13.06984

E. DEVELOPMENT OF MUTUAL INTERFERENCE CHARTS

As part of the analysis program to determine limits for equipment interference characteristics, Mutual Interference Charts (MIC) were employed. Using these charts, it is possible to tell at a glance what transmitter frequencies will interfer with a given receiver frequency, and what receiver frequencies are susceptible to a given transmitter frequency. The computer program (MSTR2) developed for this contract was used to develop this chart.

Mutual Interference Charts allow one to tell what the interference susceptible frequency ranges are for a particular equipment deployment. For an example, see Figure 21. Assuming a receiver and transmitter with the specifications listed in Table 8, a receiver with a center frequency of 30.25 GHz will be suscepible to the transmitter operating in the frequency range of 30.1 to 30.4 GHz. The receiver frequency is read on the vertical axis and the transmitter frequencies along a horizontal line at f = 30.25 GHz.

The MIC of Figure 21 represents a one-way interference condition. It indicates a condition where a receiver is tunable from 30.25 to 30.4 GHz and indicates the transmitter frequencies which will interfer with the receiver at any frequency in that range. A two-way chart would include a tunable transmitter also and will indicate what which receiver frequencies will be interfered by each given transmitter frequency. This can be accomplished by continuing the diagonal lines to cover the range of transmitter tunable frequencies.

The MIC is developed by holding the receiver frequency constant while varying the transmitter output frequencies. The transmitter frequencies where interference first appears mark the horizontal limits at the fixed receiver frequency. If the horizontal and vertical axis are the same scale, then 45 degree lines are drawn as shown. The resulting shaded area is the interference region.

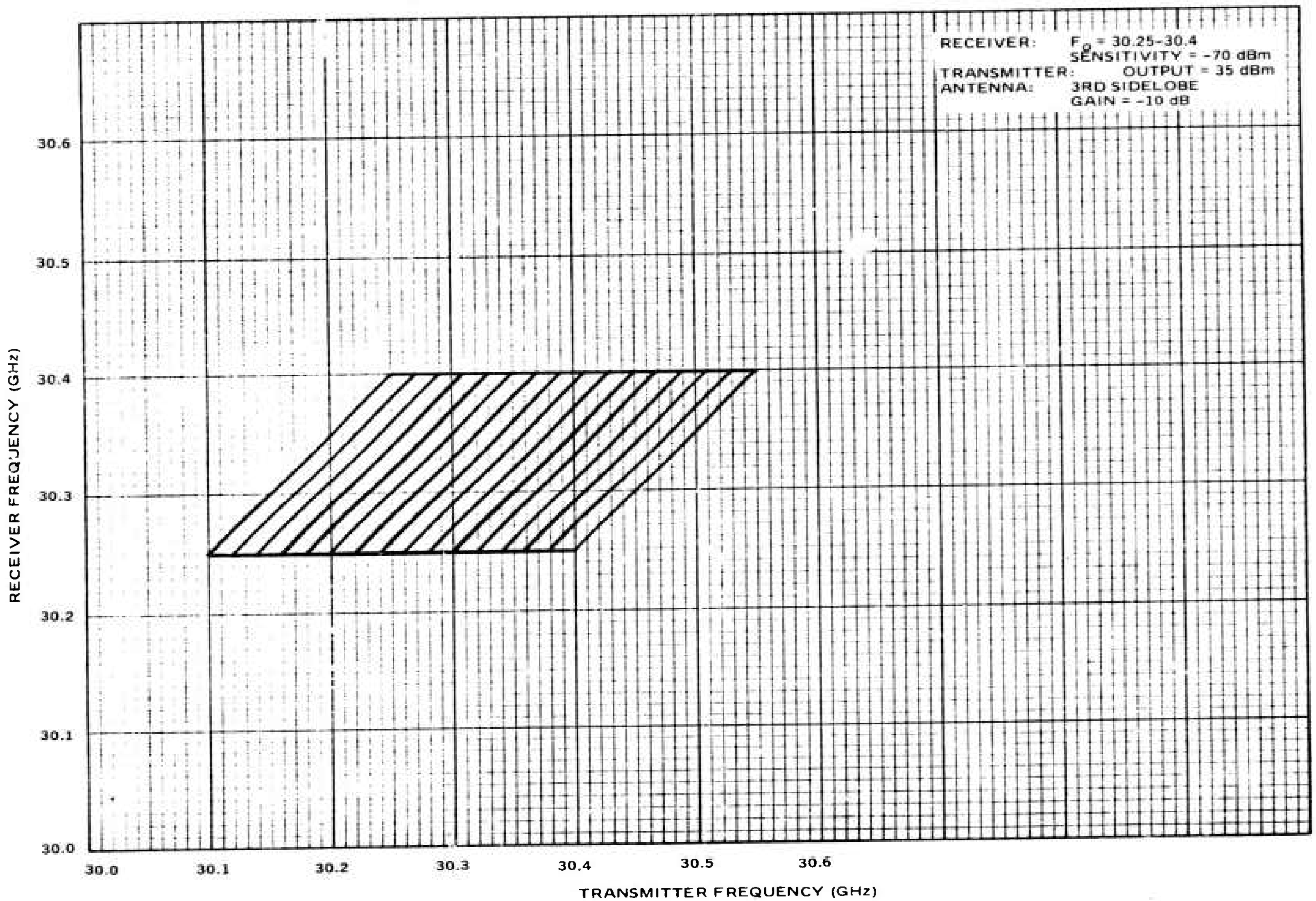


Figure 21. Mutual Interference Chart

TABLE 8. DESCRIPTION OF EQUIPMENT

Receiver:	F_o = 30. 25 - 30. 4 GHz 3 dB Bandwidth = ±200 MHz Sensitivity = -70 dBm Skirt Selectivity = -30 dBm, ±600 MHz Band Edges = 30, 30. 5 GHz at 10 dBm
Transmitter:	F_o = 30. 0 - 30. 6 GHz Output = 35 dBm 3 dB Bandwidth = ±2. 5 MHz Skirt Edges = ±5 MHz at -55 dBm Band Edges = -120 dBm
Antenna and Propagation	Equipment coupled by 3rd sidelobe; Antenna Gain = -10 dB Antenna Separation = 10 meters

IV. MILLIMETER WAVE EMC TESTING

In the process of generating recommendations for the millimeter wave EMC specification it is important to consider the many aspects associated with millimeter wave EMC testing. Consideration must be given to the propagation and coupling properties of millimeter waves. Other important considerations include: operational characteristics of millimeter wave components, intended function of the millimeter wave system being evaluated, economic factors, the testing area, and collocated systems.

A. INTERFERENCE EMISSION AND SUSCEPTIBILITY TESTING

Interference emission and susceptibility tests specified in present military standards include powerline and signal/control line conducted tests, case and cable radiated emission, antenna spurious and harmonic radiated tests. Results obtained during the experimental portion of the study indicate that the case radiations and antenna spurious and harmonic radiations of millimeter wave systems are similar in character to those of lower frequency systems and should be measured at frequencies up to 100 GHz (reference 3). Experiments indicate however that conducted emissions do not readily couple or propagate on typical powerline or signal/control lines at millimeter wave frequencies (reference 2). Millimeter wave systems should be tested to the conducted emission requirements of MIL-STD-461 which includes testing to 50 MHz, since low frequency conducted emissions occur in millimeter wave systems due to the presence of these low frequencies in power supplies and modulators. These conducted emissions tests should be required only when these emissions can cause interference and noise problems such as when collocated with low frequency communication systems.

1. Tailoring of EMC Requirements

Tailoring of interference emissions and susceptibilities should be considered for special millimeter wave system applications. A conducted interference requirement of total noise on power lines may represent a more meaningful requirement than the requirement for conducted current on small systems which are self-contained power lines. The total noise requirement would be stated in terms of peak-to-peak voltage on the power lines and would be based upon susceptibility characteristics of the millimeter wave components within the system.

A more complete discussion on development of tailoring rationale for the MIL-STD-461 and 469 tests is found in Section VI of this report. Development of the specification recommendations included consideration of the state-of-the-art of millimeter wave component technology. They did not include consideration for limitations of presently available test instrumentation in areas where it was apparent that improvements could be accomplished by proper utilization of state-of-the-art components.

V. EMC TEST INSTRUMENTATION

A. EQUIPMENT EMPLOYED DURING THE STUDY

Test instrumentation employed during the Millimeter Wave EMC Study consisted of Millimeter Wave EMC receivers, IMPATT diode sources, backward wave oscillators, klystron generators and spectrum analyzers. These devices employed external mixers with attached millimeter wave antennas. The mixer/antenna unit was connected to the receiver and analyzer via a coaxial cable. This arrangement enabled the antenna/mixer unit to be hand held and readily moved about to intercept the millimeter wave emissions. Portable EMI receivers were employed for field measurements. Spectrum analyzers and EMI receivers were both employed in laboratory tests.

Large signal inputs to millimeter wave mixers was avoided to prevent excessive spurious response problems. The mixers employed very high order harmonics of the local oscillator located in the receiver unit. Quality of the mixers vary greatly in sensitivity. A mixer with a sensitivity of -70 dBm was fabricated for use in the 70 to 100 GHz range. Sensitivities of mixers in the 20 to 70 GHz range were found to be typically -70 dBm.

B. DESIRED EMC RECEIVER DESIGN

An EMC receiver design that would have desirable features for millimeter wave EMC measurements is shown in Figure 22. This receiver would have a local oscillator/mixer/antenna unit of a size which could be hand held. The local oscillator would consist of plug ins covering the frequency range of 26 to 100 GHz. This receiver would exhibit improved spurious response characteristics since its mixer would not be operating at high order harmonics of the local oscillator. The local oscillator would operate at a frequency near the tuned frequency, possibly within 100 MHz. Local oscillator tuning voltages would be provided from the receiver. Accurate frequency readout would be provided.

A millimeter wave receiver is being developed for use in a space flight application which could be adapted to serve as an EMC receiver. This receiver covers the frequency range from 22 GHz to 55 GHz and could be extended to 100 GHz through use of the plug in local oscillator/mixer units. A block diagram of this receiver is shown in Figure 23.

1. Electrical Performance

Typical electrical performance, is as follows:

a. Maximum RF input voltage standing wave ratio: 1.5:1

b. Local oscillator drive power: 6 mW max.

c. RF to LO isolation: 20 dB

d. Intermediate frequency: 60 MHz

e. Intermediate frequency – 1.0 dB bandwidth: 10-110 MHz

f. Intermediate frequency ripple: ±0.5 dB maximally flat

g. Intermediate frequency skirt selectivity: -30 dB minimum 1 MHz and above 120 MHz

h. Intermediate frequency compression: less than 1 dB for -10 dBm IF output

i. RF to IF gain: 30 dB minimum

j. IF amplifier noise figure: 1.2 dB

k. Intermediate frequency output VSWR: 1.5:1 maximum into 50 ohms

l. Overall mixer preamplifier gain stability: ±0.5 dB, 0 to 50°C

m. DC input voltage: +15 volts

n. DC power requirement: 0.4 watt maximum

o. IF output connector: OSM jack

p. DC power and crystal monitor connectors: feedthrough solder terminals

q. Shielding of external frequencies 5 to 500 MHz: greater than 120 dB

r. Crystal current power requirement: None

s. Crystal current monitor: voltage probe at RFI filter output

2. RF Performance

Typical RF performance for the individual channels:

<u>V-Band</u>

a. RF input frequency: 52.0 to 56.0 GHz min (0.5 dB points)

b. RF input bandwidth: 0.5 GHz

c. Overall mixer-preamplifier double side-band noise figure: 5.0 dB

<u>R-Band</u>

a. RF input frequency: 31.4 GHz

b. RF input bandwidth: ±200 MHz minimum (0.5 dB points)

c. Overall mixer-preamplifier double side band noise figure: 4.0 dB

K-Band

a. RF input frequency: 22.235 GHz

b. RF input bandwidth: ±200 MHz minimum (0.5 dB points)

c. Gain Flatness: ±1.0 dB

d. Noise Figure: 2.5 dB max

e. Detector Sensitivity: 500 mV/mW

f. Voltage Controlled Attenuator: 0 to 20 dB

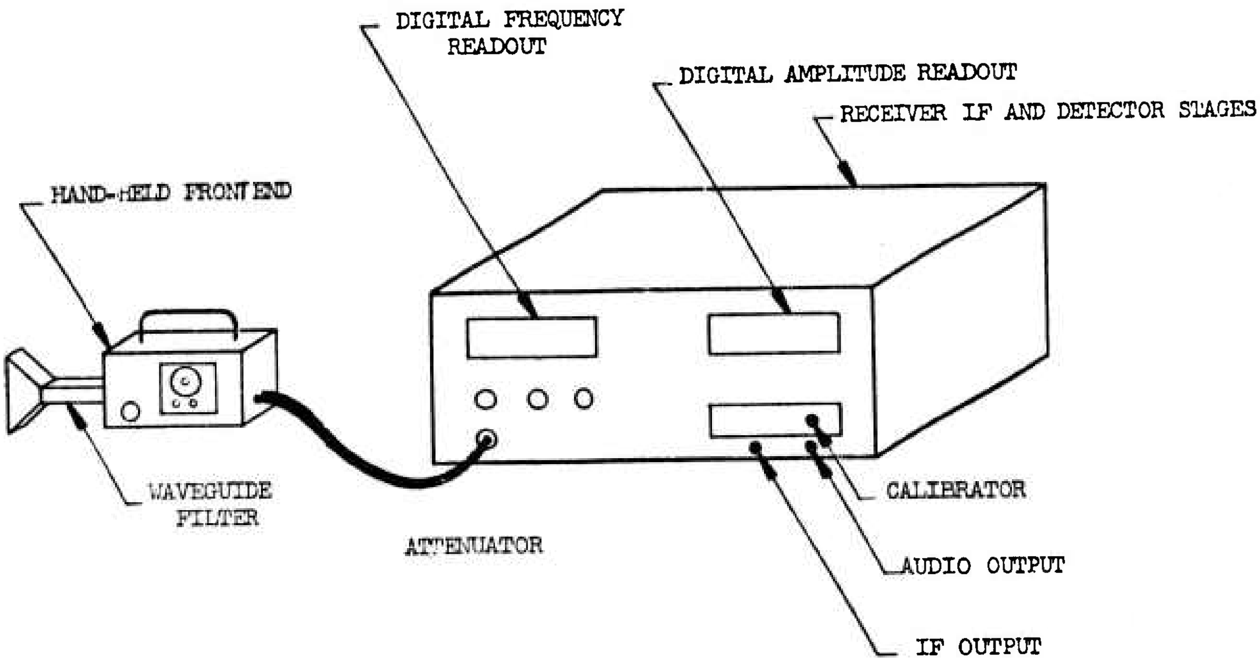


Figure 22. MM-Wave EMC Receiver Configuration

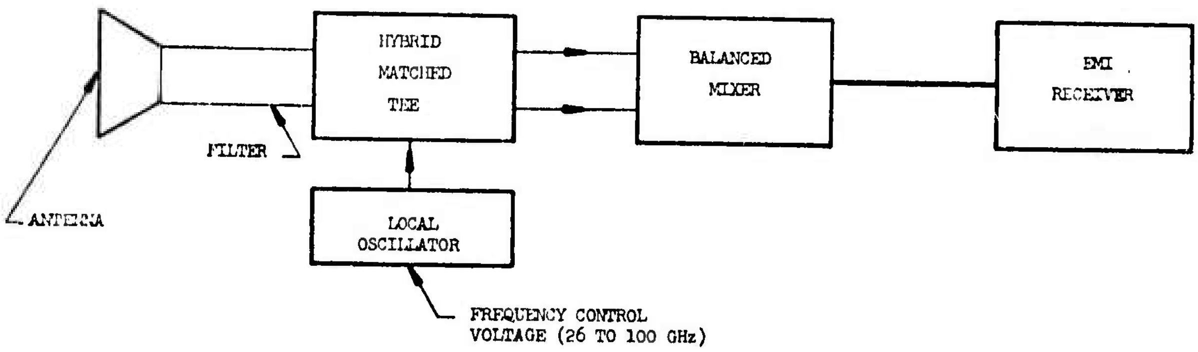


Figure 23. Block Diagram of MM-Wave EMC Receiver

3. Local Oscillator

The local oscillator proposed to be furnished with this receiver will consist of a solid state source (Gunn or IMPATT diode), a ferrite isolator and an attenuator.

4. Environmental Criteria

The receiver system will be designed to operate under the following conditions.

Temperature range: -30°C to +50°C

Humidity Condition: 100% RH

Vibration Conditions: MIL-STD-810B, Notice 1, par 4.6.1, Part 1, Curve AR of Figure 514.1-2. (Reference 18)

5. Extension of Frequency Range to 100 GHz

In order to identify the fundamental frequencies and strength of any signals in the millimeter-wave frequency range from Ka-Band through W-Band (22.6 – 110 GHz) for EMC applications, the conventional method of harmonic mixing using a fixed frequency LO becomes costly and difficult. Since IMPATT diode oscillators have negative resistances over a wide frequency range, any properly designed RF circuit would enable the construction of a single swept frequency oscillator to cover the full waveguide band. The use of a full waveguide band swept frequency IMPATT oscillator as a local oscillator provides a very simple and efficient way for rapid frequency scanning and signal identification. Such full band swept frequency oscillators using double-drift IMPATT diodes are under development at the present time. The major portion of the millimeter-wave bands can be covered with two oscillators using single-drift IMPATT diodes which are somewhat narrower in bandwidth than the double drift diodes. However, full band oscillation with one single-drift IMPATT diode has already been observed in both Ka-band (22.6 – 40 GHz) and V-band (50 – 75 GHz).

Figure 24 shows a millimeter-wave multi-band receiver circuit schematic covering 22.6 to 110 GHz using four full band swept frequency local oscillators. The bias current of the local oscillator is controlled to achieve frequency scanning either automatically or manually. In addition four fixed frequency IMPATT oscillators are provided for signal strength calibration. The oscillators are normally terminated with resistive loads to prevent leakage into the mixer.

The all solid-state millimeter-wave multi-band receiver would be compact in size, with the least amount of RF components, reliable, and most of all able to provide fast and accurate signal identification.

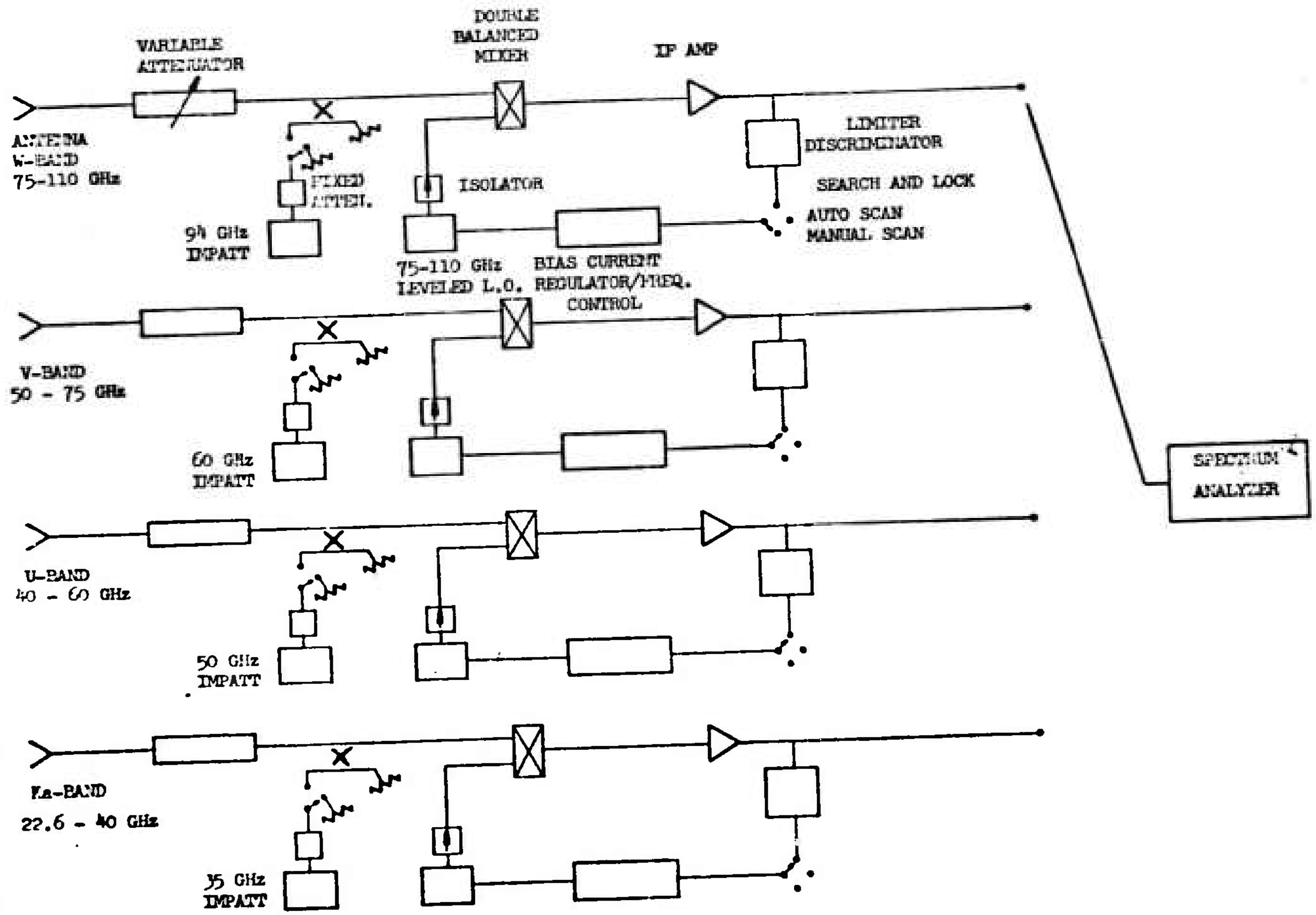


Figure 24. Schematic of Proposed 22.6 to 110 GHz EMC Receiver

VI. DEVELOPMENT OF RATIONALE FOR THE EMC SPECIFICATION

A. BASIC APPROACH

It seems evident to one gathering data on millimeter wave system EMC characteristics that a basic specification requirement should be combined with allowances for special operational conditions. Millimeter wave systems in their basic form exhibit interference characteristics which can be predicted with reasonable accuracy. A basic form of millimeter wave system is considered to represent a typical system in its simplest configuration. A typical basic millimeter wave receiver can be illustrated as an example. This receiver consists of a mixer, local oscillator, intermediate frequency amplifier and detector. Often there are no preselectors or front end filters provided. These basic receivers are being used successfully in numerous millimeter wave applications without encountering interference problems. As this study has shown the occurrence of interference interactions in millimeter wave systems is reduced considerably from those encountered at lower frequencies. (However, there are specific applications where special techniques such as waveguide filters must be provided to avoid interference problems. An example of a special case of this type is one where high powered adjacent channel systems are collocated in a millimeter wave system configuration.

B. EMC TEST CATEGORIES

1. Millimeter Wave System Classification

It is recommended that EMC test requirements for millimeter wave systems be categorized according the system deployment and functional requirements. The typical types of millimeter wave systems that may fall in any of the classifications are listed below:

1. <u>Communication Systems</u> – Communication systems are commonly found in the V bands, Ka bands and lower frequencies. V band systems are usually limited to secure communication applications. MIL-STD-461 tests and limited MIL-STD-469 tests are recommended for communication systems.

2. <u>Radar Systems</u> – Radar systems are found usually in the W band, Ka band and lower bands. MIL-STD-469 and MIL-STD-461 A tests are recommended for radars.

3. <u>Radiometer Systems</u> – Radiometer systems may be employed at any frequency between 20 GHz and 100 GHz or higher. MIL-STD-461 and limited MIL-STD-469 tests are recommended for radiometer equipment.

4. <u>Monitor Systems</u> – Monitor systems may be employed at all millimeter wave frequencies. MIL-STD-461 and limited MIL-STD-469 tests are recommended for monitor systems.

2. Millimeter Wave System Deployments

The electromagnetic environment of the intended deployment of a specific millimeter wave system should play an important role in the EMC testing requirements to be imposed upon that system. Frequency ranges of testing should be in direct relationship to the frequency range of the deployment environment. It is important to control the frequency range of testing in millimeter wave systems to avoid overtesting for economic reasons. The cost of millimeter wave EMC testing is relatively high compared to lower frequency testing.

a. Mixed Low Frequency and Millimeter Wave Deployments – EMC test requirements for millimeter wave systems intended for use in multifrequency mixed deployments should include the wide range of test frequencies of MIL-STD-461/462 in addition to the applicable millimeter wave frequencies. Examples of required low frequency testing are conducted emissions, conducted susceptibility, radiated emissions and radiated susceptibility. Results of this study indicate that conducted emission and susceptibility tests need not be extended beyond the frequency range requirements of MIL-STD-461/462. All classifications listed in Section VI-B-1 can be expected to be employed in a multifrequency mixed deployment.

b. Multifrequency Millimeter Wave Deployment – Systems planned for use in multifrequency deployments limited to millimeter wave systems need not be subjected to the wide range of test frequencies specified in MIL-STD-461/462. Powerline conducted emissions tests of MIL-STD-462 would not be required. Powerline conducted emission and susceptibility tests would be limited to the necessary tests required to verify compatibility with the noise and transient characteristics of the power line. Radiated emissions and susceptibility tests should be limited to the millimeter wave frequency ranges being employed in the deployment.

c. Single Band Millimeter Wave Deployment – EMC test requirements for millimeter wave systems planned for use in single frequency band applications can be reduced to a minimum. EMC testing of these systems would consist mainly of system compatibility tests. Out-of-band testing would be eliminated. Powerline conducted emission and susceptibility tests would again be limited to those tests necessary to verify compatibility with the power bus noise and transient characteristics.

d. Millimeter Wave System Functions – The system/equipment classification guidelines of MIL-STD-461 should be employed in establishing the severity of millimeter wave EMC test requirements. Classes A, B and C only are considered applicable to millimeter wave systems. These classes are described as follows:

Class A – Primary mission subsystems/equipment which must operate together for mission success.

1. ground communications/electronics facilities

2. spacecraft equipment

3. aircraft equipment

Class B – Direct support subsystems/equipments.

1. AGE, checkout of aircraft

2. AGE, checkout of spacecraft

3. communication/electronics support equip.

4. trainers and simulators

Class C – Support subsystems/equipments beyond coupling range of primary mission equipment.

1. test equipment

2. navigation aids

3. monitoring equipment

4. AGE used away from flight line

e. Tailoring of Millimeter Wave EMC Requirements – It is recommended that EMC requirements be tailored for millimeter wave systems. Tailoring criteria should employ considerations of the system classification, application, deployment and functions described in VI-B-1, 2, 3 and 4. Tailoring of the requirements may relax the requirements of this document to the point of deleting the test and will depend upon the combination of these aspects as they apply to the system being evaluated. Especially severe requirements can be established for those special systems where the criteria establishing aspects justify such tailoring. An example of this condition is found in MIL-STD-461A, Notice 3, where a radiated susceptibility requirement of 200 volts per meter from 10 GHz to 40 GHz has been established for subsystems/equipments to be installed on external aircraft mounting. This requirement represents a 20 dB increase over the normal MIL-STD-461 radiated susceptibility requirement of 20 volts/meter. Conversely MIL-STD-461, Notice 3 permits relaxation of requirements for subsystems/equipments when the particular program applications do not represent severe interference conditions. Deletion of certain tests are permitted when systems analysis based on coupling, antenna locations, shielding, materials, etc indicates the need for these tests does not exist.

3. Examples of Typical EMC Test Requirements

Examples of procedures for establishing EMC requirements for typical millimeter wave systems are as follows.

a. Example 1 – A type 1 deployment consisting of a 30 GHz millimeter wave communication system is operated with high powered collocated systems operating in the 1 to 5 GHz frequency range. The millimeter wave system must operate in the field of the main beam of the collocated system. This field is found to be equal to 200 volts/meter. Both systems are operated from common power sources. The millimeter wave system performs a Class A function which warrants the most stringent requirements.

Recommended EMC requirements for this millimeter wave system are as follows:

Conducted Emissions – Apply the conducted emission requirements of MIL-STD-461 to powerlines and interfacing signal/control cables.

Powerline Conducted Susceptibility – Apply the powerline susceptibility test requirements (CS01, CS02 and CS06) of MIL-STD-461. The purpose of these tests is to verify operation of power supplies with typical power sources.

Radiated Emission – Radiated emission tests shall be performed in the 1 to 5 GHz range to verify compatible operation with the collocated system. These tests may be deleted if it can be shown there are no generators of these frequencies in the millimeter wave system. Antenna spurious and harmonics can be deleted.

Radiated Susceptibility – Tests should be performed to verify successful operation of the millimeter wave system when exposed to 200 volts/meter at 1 to 5 GHz. The millimeter wave system shall be tested with its receiver antenna directly in the main beam of the collocated system if this type of operation is required. Radiated susceptibility tests shall be at the harmonic frequency of the collocated system nearest to the millimeter wave system operating frequency. A value of 110 dB/uV/ meter is the recommended level for high order harmonic susceptibility tests based upon results of this study (reference 3). The receiver susceptibility test at millimeter frequencies may utilize signal injection at the receiver input such as CS03, CS04 and CS05 test methods of MIL-STD-462. The signal levels applied at the antenna waveguide input may be determined by calculation of the receiving antenna aperture and utilizing this antenna factor to establish the receiver input level, which would occur due to the radiated field.

b. Example 2 – A type 2 deployment consisting of a 60 GHz millimeter wave communication system is operated with a 30 GHz collocated millimeter wave communication system. The systems are deployed such that both are located at least six degrees outside the main beams of the collocated system. Each system is operated on separate power sources. Both systems perform a Class B function.

Recommended EMC requirements for this millimeter wave system are as follows.

Conducted Emissions – Conducted emissions tests are not required since there arc no common powerlines.

Conducted Susceptibility – Powerline conducted susceptibility tests shall be performed only to the extent that is necessary to assure compatible operation with the power source.

Radiated Emission – Radiated Emissions of each system shall be performed in the operating frequency range of the collocated system. The 30 GHz system shall be tested for antenna harmonic and spurious emissions in the 60 GHz frequency range of the collocated system.

Radiated Susceptibility – Both systems shall be tested for radiated susceptibility signals in the frequency range of the collocated system.

c. Example 3 – A type 3 millimeter wave system would have the least stringent requirements. The only test required would be a compatibility test to determine that intra-system compatibility has been achieved. The compatibility test may consist of conduction of a functional performance verification test.

If assurance of compatible operation is desired prior to a functional performance test conducted susceptibility tests can be performed to verify successful operation with the power source noise and transient characteristics. Receiver susceptibility tests can also be performed to verify adjacent channel rejection characteristics.

4. Test Requirements Table

Tables 9 and 10 contains a test requirements list for the following categories of millimeter wave systems:

1. Functional Classification

   Class A – Primary Mission Equipment

   Class B – Direct Support Equipment

   Class C – Support Equipment Beyond Coupling Range

2. Deployment Type

   Type 1 – Multifrequency Mixed Deployment

   Type 2 – Multifrequency Millimeter Wave Deployment

   Type 3 – Single Band Millimeter Wave Deployment

Tables 9 and 10 are submitted as guidelines for determining EMC test requirements of millimeter wave systems.

TABLE 9. MODIFIED MIL-STD-461 TEST REQUIREMENTS APPLICABLE TO MM-WAVE SYSTEMS

Class Function	A			B			C		
Deployment Type	1	2	3	1	2	3	1	2	3
CE01, 0.03 to 50 KHz, Power Leads DC	Y	T	T	Y	T	T	Y	T	T
CE02, 0.03 to 50 KHz, AC Power Leads	Y	T	T	Y	T	T	Y	T	T
CE03, 0.03 to 50 KHz, Control/Signal Leads	Y	T	T	Y	T	T	Y	T	T
CE04, 0.05 to 50 MHz, Power Leads	Y	T	T	Y	T	T	Y	T	T
CE05, 0.05 to 50 MHz, Control/Signal Leads	Y	T	T	Y	T	T	Y	T	T
CE06, 10 KHz to 10.0 GHz, Spurs and Harmonics	N	N	N	N	N	N	N	N	N
CS01, 0.03 to 50 KHz, DC Power Leads	Y	T	T	Y	T	T	T	T	T
CS02, 0.05 to 400 MHz, Power Leads	Y	T	T	Y	T	T	T	T	T
CS03, 10 to 100 GHz, Intermodulation	Y	Y	T	Y	Y	T	T	T	T
CS04, 10 to 100 GHz, Rejection of Undesired Signals	Y	Y	T	Y	Y	T	T	T	T
CS06, Spike, Power Leads	Y	T	T	Y	T	T	T	T	T
CS07, Squelch	Y	Y	Y	Y	Y	Y	Y	Y	Y
RE01/RE04, 30 Hz to 30 KHz, Magnetic Field	T	T	T	T	T	T	T	T	T
RE02, 14 KHz to 100 GHz, Electric Field	Y	T	T*	Y	T	T*	T	T	T*
RE03, 10 to 100 GHz, Spurs and Harmonics	Y	Y	T	Y	Y	T	T	T	T
RS01, 30 Hz to 30 KHz, Magnetic Field	N	N	N	N	N	N	N	N	N
RS02, Magnetic Induction Field	T	T	T	T	T	T	T	T	T
RS03, 14 KHz to 100 GHz, Electric Field	Y	T	T*	Y	T	T*	T	T	T

Y = Yes
T = Tailored to program (adjustment of frequency range and level of test)
N = No
* = Tailoring of frequency range

TABLE 10. MODIFIED MIL-STD-469 TEST REQUIREMENTS APPLICABLE TO MM-WAVE RADAR SYSTEM

Class Function		A			B			C	
Deployment Type	1	2	3	1	2	3	1	2	3
6. 2, Transmitter Frequency Tolerance 10 to 100 GHz	Y	Y	Y	Y	Y	Y	Y	Y	Y
6. 3, Maximum Emission Bandwidth 10 to 100 GHz	Y	Y	Y	Y	Y	Y	Y	Y	Y
6. 4, Tunability 10 to 100 GHz	Y	Y	Y	Y	Y	Y	T	T	T
6. 5, Antenna Sidelobe Supression 10 to 100 GHz	Y	Y	Y	Y	Y	Y	Y	Y	Y
6. 6, Spurious Radiations 10 to 100 GHz	Y	Y	Y	Y	Y	Y	Y	Y	Y
6. 7. 1, Receiver Acceptance Bandwidths 10 to 100 GHz	Y	Y	Y	Y	Y	Y	Y	Y	Y
6. 7. 2, RF Preselection 10 to 100 GHz	T	T	T	T	T	T	T	T	T
6. 7. 3, Receiver Stability 10 to 100 GHz	Y	Y	Y	Y	Y	Y	Y	Y	Y
6. 7. 4, Receiver Radiation 10 to 100 GHz	T	T	T	T	T	T	T	T	T

Y = Yes
T = Tailored to program

5. Rationale for Table 9 Recommendations

The following philosophy was employed in establishing the recommendations of Table 9 for MIL-STD-461 type testing of millimeter wave systems.

a. Conducted Emissions – Strict adherence to the powerline and signal line conducted emission requirements of MIL-STD-461 is considered important for the multifrequency mixed low frequency and millimeter wave system deployment. Control of conducted emissions on cables produced by interference sources such as power supplies and modulation pulses are considered important in deployments containing low frequency receivers. These conducted emissions may cause interference in the lower frequency systems. No extension of the MIL-STD-461 frequency range requirements is recommended for millimeter wave systems due to the lack of millimeter wave signal coupling on cables.

Tailoring of conducted emission test requirements for millimeter wave systems in the deployments containing millimeter wave systems only is recommended as the type of emissions capable of being propagated on cables are of frequencies well below millimeter wave frequencies and will not cause receiver interference. Tailoring may consist of limiting conducted emissions to power buss noise specifications only.

b. Antenna Spurious and Harmonic Emissions – These tests are not recommended for millimeter wave systems. It is not feasible to attempt to perform waveguide measurements of spurious and harmonic emissions at millimeter wave frequencies due to the problems encountered in obtaining meaningful measurements when employing waveguide transitions to test instrumentation equipment MIL-STD-461A recognizes this fact and does not recommend CE06 measurements above 1.24 GHz.

If in-band receiver emissions are of concern they should be tailored to program requirements.

c. Powerline Conducted Susceptibility – Strict adherence to the conducted susceptibility requirements of MIL-STD-461 is considered important in the mixed multifrequency deployments for Class A and Class B systems. It is recommended that these requirements be tailored for all other millimeter wave applications. Single frequency band deployments and all Class C systems will not experience cable coupled RF signals. Tailoring of the requirements to meet the power buss noise and transient specification is suggested. A typical example is that level which has been successfully applied in spacecraft requirements of 10 mv peak to peak noise and 2 volt transient on a powerline having a source impedance of 0.1 ohm. This requirement represents a total noise level and is not frequency dependent as the MIL-STD-461A requirement states.

d. Receiver Susceptibility – Compliance to intermodulation and rejection of undesired signal requirements are considered important for

multifrequency deployments in Class A and B systems. It is recommended that receiver susceptibility requirements for single frequency band millimeter wave systems be tailored to include rejection of adjacent channel signals only. The requirements of Class C systems can be tailored to provide assurance that intra-system compatibility of the Class C system only is achieved.

e. Squelch – The squelch requirement of MIL-STD-461 is applicable to all receivers since it enhances the operation and provides for the comfort of the operator therefore it is recommended for all types of systems and deployments.

f. Radiated Emissions – Radiated magnetic field emissions shall apply only to those systems which are operated in the very near vicinity of highly sensitive magnetic devices. Therefore tailoring of this requirement is suggested for all types of systems and deployments. Radiated electric fields emanating from cables and equipment enclosures are recommended to meet requirements of MIL-STD-461 to 10 GHz and requirements of this document from 10 to 100 GHz. The frequency range of test may be tailored for the multifrequency and single band millimeter wave deployments for Class A and B systems. The limits and frequency ranges may be tailored for all Class C systems. A tailoring of Class C systems requirements to assure intra-system compatibility is suggested. It is suggested that bandwidth considerations be added to RE03 requirements.

g. Radiated Susceptibility – It is recommended that the radiated magnetic susceptibility requirements be tailored to the program for all millimeter wave systems. This test should not be performed on a millimeter wave system unless it is definitely determined that the system will be exposed to a magnetic filled environment and also determined that the system contains elements which are subject to being affected by these magnetic fields. Magnetic fields exist predominantly at low frequency and will not affect millimeter wave generating equipment. The elements of millimeter wave systems which may be affected by the magnetic fields of RS01 and RS02 include modulators and read out devices.

It is recommended that all Class A and B millimeter wave systems be tested to radiated electric field requirements of MIL-STD-461 and this document. The tailoring notation of Table 9 for Class B and C denotes the suggestion that the test frequency range for multifrequency and single band millimeter wave systems be tailored to the frequencies employed in those deployments. Tailoring of Class C requirements to assure compatibility of the equipments is recommended since these equipments are considered out of coupling range of primary mission systems.

6. Rationale for Table 10 Recommendations

The following philosophy was employed in establishing the recommendations of Table 10 for MIL-STD-469 type testing for millimeter wave systems. MIL-STD-469 includes certain requirements at frequencies up to 40 GHz. No

recommendations for changes in these requirements are made in this document. Other requirements listed in Table 10 are given for the frequency range of 10 to 100 GHz.

a. Transmitter Frequency Tolerance – Compliance to the transmitter frequently tolerance requirements is recommended for all deployments and system classifications. Frequency control of radar systems is considered important in all applications including support equipment. This control is necessary to obtain reliable information from the radar data. It is considered important that all radar classifications meet frequency tolerance requirements. The reason for this is the fact that elevation of radars vary over large angles can lead to interference of air and space craft systems.

   The frequency tolerance requirements of MIL-STD-469 are not severe and compliance to this requirement should not cause undue difficulty in achieving compliance.

b. Maximum Allowable Radar Emission Bandwidth – The requirements for MIL-STD-469 for maximum allowable bandwidth are reasonable for the types of modulations addressed. There are other types of modulation techniques being employed in modern radars which need further definition in regard to millimeter wave radars. Further investigation of the impact of these radar techniques on emission bandwidths is recommended for future study. Compliance to emission bandwidth is considered important for all radar classifications for the interference control conditions of high elevation angle radars as described in the preceeding discussion of 6-a.

c. Tunability – Tunability is considered important for all millimeter wave radars except Class C. All radars associated with primary mission systems must be compatible in tunability abilities to provide satisfactory operation. Radar equipment employed in support equipment not related to the primary mission equipment may be tailored to meet its particular functional operation requirements.

d. Antenna Side Lobe Suppression – All millimeter wave radars are recommended to comply to the antenna side lobe suppression requirements of MIL-STD-469 to avoid interference at all angles of elevation. The side lobe requirements of MIL-STD-469 were found to be commensurate with millimeter wave antenna characteristics investigated in this study.

e. Spurious Radiations – It is recommended that all millimeter wave radar comply to spurious radiations to control interference at all angles of elevation. The trend of MIL-STD-469 in increasing the spectral level with increase in frequency is followed in this document.

f. Receiver Acceptance Bandwidths – Compliance to receiver acceptance bandwidth requirements of MIL-STD-469 are recommended for all classes of millimeter wave radars. It is important that the receiver acceptance bandwidth be compatible with radar transmitter emission bandwidths as MIL-STD-469 indicates.

g. RF Preselection – It is recommended that the MIL-STD-469 requirement for RF preselection be tailored for all classes of millimeter wave radars. The reason for this recommendation is based upon the lack of preselection devices for millimeter wave systems. This limitation of millimeter wave equipments should be considered in establishing frequency allocations for millimeter wave radars.

h. Receiver Stability – The requirement of MIL-STD-469 that receiver stability be commensurate with associated transmitters is self explanatory since this is a necessary requirement to achieve satisfactory operation of a radar system.

i. Receiver Radiation – The effects of radar receiver radiation is subject to variable factors such as antenna characteristics and deployments. It is recommended that this requirement be tailored to the programs for all classes of millimeter wave radars.

C. DEVELOPMENT OF RECOMMENDED SPECIFICATION LIMITS

Results of the literature search, experiments and analysis conducted during this program have been combined to provide the basis for the following recommended specification limits.

Extension of MIL-STD-461 Requirements

1. CE01, CE02 and CE04, Conducted Emission, 0.03 to 50 kHz, Power Leads

Limits of Figure 4, 5, and 6, MIL-STD-461A, Notice 4 are recommended for Millimeter Wave Systems used in Type I, mixed multi-frequency deployments. This limit represents a reasonable value to be imposed on systems to prevent lower frequency emissions which may cause interference to communication systems operating in the deployment.

Tailored limits are recommended for all other millimeter wave systems. A value which has been employed successfully on millimeter wave systems is 10 milliwatts peak to peak total noise on a power buss 0.1 ohms source impedance (Reference 13).

2. CE03 and CE05, Conducted Emissions, 0.03 to 50 kHz, Control/Signal Leads

The limits of Figures 4, 5 and 6 MIL-STD-461A, Notice 4 are recommended here also for Type I systems for the same reasons given for CE01, CE02 and CE04. Naturally the limit must be tailored to allow for the intentional transmissions on signal leads as indicated in MIL-STD-461A. MIL-STD-461A limits shall apply when the intentional transmission spectrum levels are lower than those of MIL-STD-461A.

Limits for Types 2 and 3 systems may be tailored to system compatibility requirements.

3. CE06, Antenna Conducted Emissions, 10 kHz to 10 GHz

This test is not recommend for reasons described in VI-B-5-b of this document.

4. CS01 and CS02, Conducted Susceptibility, 30 Hz to 400 MHz, Power Leads

It is recommended that Type 1 of Class A and B millimeter wave systems meet the requirements of Figures 8 and 19, MIL-STD-461A, Notice 4. All other millimeter wave systems may be required to meet powerline conducted susceptibility requirements tailored to the program. As stated in VI-B-2-e of this document, a typical tailored test could consist of a total noise level of a peak to peak voltage from a source impedance equivalent to the power source intended for use with the millimeter wave system.

5. CS03, Intermodulation, 10 to 100 GHz

It is recommended that types 1 and 2, Classes A and B millimeter wave receivers be specified to meet the requirements of 6.7 of MIL-STD-461A, Notice 4. This requirement states that receivers shall not develop intermodulation products when exposed to out-of-band signals 66 dB above the level

required to produce a standard response. Results of experiments performed during this study indicate that many millimeter wave systems will not meet this requirement unless filters are installed at the antenna input (Reference 2). However later experiments indicate that millimeter wave systems can be expected to experience signals of comparable levels when operating at locations equivalent to the fourth antenna side lobe of collocated systems (reference 3). Other types and classes of millimeter wave systems are recommended to meet intermodulation requirements tailored to the program.

6. CS04, Rejection of Undesired Signals, 10 to 100 GHz

It is recommended that types 1 and 2, Classes A and B millimeter wave systems meet the requirements of 6.9, MIL-STD-461A, Notice 4. This requirement states that operation of receivers shall not be degraded when exposed to out-of-band signals 80 dB above the level required to produce a standard response. The curve of Figure 9 should be tailored to the program since the bandwidth of millimeter wave system receivers may in some instances be wider than that stated in the figure by necessity. Other types and classes of millimeter wave systems should have requirements which are tailored to the program.

7. CS06, Spike, Power Leads

This test is recommended for the same systems as CS01 and CS02 with the same rationale. The transient of Figure 10, MIL-STD-461A, Notice 4 is recommended. For the systems which are recommended for tailoring, the transient shall be revised to a value that represents typical transients found on the power buss.

8. CS07, Squelch

The requirements of 6.11, MIL-STD-461A, Notice 4 is recommended for all types and classes of millimeter wave systems.

9. RE01/RE04, 30 Hz to 30 KHz, Magnetic Field Emissions

It is recommended these tests be limited to only those millimeter wave systems that are intended for operation in the vicinity of sensitive magnetic devices. Tailoring of the magnetic field requirements should be adjusted to the susceptibility levels of those devices.

10. RE02, 14 KHz to 100 GHz, Electric Field

Recommended electric field emissions from cables and cases are shown in Figures 25 through 28. The limits of Figures 25 and 26 are recommended for a millimeter wave system (type 1) used in deployments involving mixed systems including low frequency systems. Figures 27 and 28 represent recommended limits for millimeter wave systems intended for use in deployments containing millimeter wave systems only. Tailoring of the frequency range of test to the single band of frequencies being used is recommended for type 3 systems. Three curves are shown for cases representing recommended limits for situations where the millimeter wave systems are confined to enclosures (up to 3 meters), closely confined external configurations (3 to 10 meters), and others (10 to

100 meters). A new test number RE0X is recommended for the radiated emission tests to be performed at millimeter wave frequencies only.

Broadband emission tests are considered important for millimeter wave systems because of the wideband characteristics of these systems and the EMC measuring instrumentation. Stating the limits in terms of a megahertz bandwidth is recommended as a standard requirement. This bandwidth has been established as a requirement for millimeter wave systems employed in spacecraft applications.

11. RE03, 10 to 100 GHz, Antenna Radiated Spurious and Harmonics

It is recommended that Class A and B types 1 and 2 millimeter wave systems be required to meet the requirements of Figure 7, MIL-STD-461A, Notice 4. This requirement is considered necessary for the multi frequency deployments of equipment in Class A and B systems where harmonic radiations can cause serious interference problems. This requirement is not recommended for single band deployments where harmonic radiations cannot cause interference problems. The harmonic requirements for Class C equipments can be tailored to meet the requirements of the program. In the case of millimeter wave systems where externally wide bandwidths are concerned it may be feasible to consider bandwidth in the requirements of RE03.

12. RS01, 30 Hz to 30 kHz, Magnetic Field Susceptibility

This test is not recommended for millimeter wave equipment. Millimeter wave receivers and transmitters are not susceptible to the level of magnetic fields specified in RS01. Magnetic field susceptibility tests may be specified for sensitive magnetic peripheral equipments which are intended for use in conjunction with millimeter wave systems.

13. RS02, Magnetic Induction Field

It is recommended that this test be required only for those millimeter wave systems which are intended for use in areas where they maybe exposed to powerline alternating currents and transients. The requirements of 6.12, MIL-STD-461A, Notice 4 is recommended when this test is specified.

RS03, 14 kHz to 100 GHz, Electric Field Susceptibility

This test is recommended over the entire frequency range of 14 kHz to 100 GHz for Classes A and B, Type 1 systems and the frequency range of 10 to 100 GHz for type 2 systems. The frequency range shall be tailored for type 3 and all Class C systems. MIL-STD-461A, Notice 4 levels are recommended for tests up to 10 GHz. A level of 130 dB/uV/meter is recommended for the frequency range of 10 to 100 GHz. This level is based upon results obtained during this study (reference 3).

Extension of MIL-STD-469 Requirements

1. 6.2 Transmitter Frequency Tolerance, 10 to 100 GHz

It is recommended that this test requirement be updated to include tailoring of frequency tolerance requirements. The present requirements of

MIL-STD-469 are quite lax. Present day millimeter wave radar systems are capable of frequency control tolerances of the order of 1 part in 10^{10}. In other cases, however millimeter wave systems employ very loose frequency control such as radar systems where the receiver tracks the transmitter. The present requirements with tailoring for millimeter waves are recommended.

2. 6.3 Maximum Emission Bandwidth, 10 to 100 GHz

Extension of the present requirements of MIL-STD-469 are recommended for millimeter wave systems. The present requirements are reasonable and provide sufficient control for millimeter wave emission bandwidths in systems employing the types of modulations mentioned in MIL-STD-469.

Further investigation of bandwidth emission requirements for special variable pulse radars is recommended. Detailed investigation of these radars proved to be beyond the scope of this contract. The proposed revision submitted by NAVSHIPS in August 1972 and the OTP document have several suggestions which should be considered.

3. 6.4 Tunability, 10 to 100 GHz

The requirements of MIL-STD-469 are recommended for all millimeter wave systems except Class C where tailoring to the specific needs of the program is suggested. In general, millimeter wave radar systems do meet the tunability requirements of MIL-STD-469.

4. 6.5 Antenna Side Lobe Suppression

It is recommended that millimeter wave antennas be specified to have their side lobes suppressed to meet MIL-STD-469 requirements. Most millimeter wave antennas investigated in this study had their major side lobes down 20 dB from the main beam and all other lobes at least 30 dB down from the main beam.

5. Radar Transmission Spurious Radiations

It is recommended that millimeter wave radar systems be required to meet the spurious radiation requirements of MIL-STD-469. The following extension of MIL-STD-469 requirements for spurious radiations is recommended:

fo (Within Frequency Range Of) (MHz)	(Limit of spectral level at the transmitter input) (Millivolts/kHz)	(dBm/kHz)
100 to 400	6.31×10^{-5}	-42
400 to 1,215	2.51×10^{-4}	-36
1,215 to 2,700	1.26×10^{-3}	-29
2,700 to 5,000	2.51×10^{-2}	-16
5,000 to 8,500	1.00×10^{-1}	-10
8,500 to 40,000	3.16×10^{-1}	-5

fo (Within Frequency Range Of) (MHz)	(Limit of spectral level at the transmitter input) (Millivolts/kHz)	(dBm/kHz)
40,000 to 60,000	3.16×10^{-1}	-5
60,000 to 100,000	3.16×10^{-1}	-5

It is recommended that a spectral envelope of spurious emissions be specified. It is recommended that the bandwidth be specified at the 40 dB down point. It is also recommended that further study be considered on revising this requirement to allow it to apply to modern radars and digital communication systems. The Office of Telecommunication Policy document (Reference 17) contains several recommendations of this type. One recommendation of this includes the following bandwidth criteria.

Conventional Pulse B = 2k/t
B = Emission Bandwidth (MHz)
k = Weighing Factor (Fig. 2 of OTP document)
t = Pulse width (microseconds)

6. 6.7.1 Radar Receiving Systems Required Acceptance Bandwidth

The MIL-STD-469 receiver acceptance bandwidth requirements are recommended for millimeter wave systems to assure compatibility with the associated transmitter.

7. 6.7.2 R.F. Preselection

RF preselection is not recommended for millimeter wave systems except in those situations where program requirements warrant it. Preselection devices are not readily available at millimeter wave frequencies. Many millimeter wave systems are presently operating successfully without preselectors. Band pass filters are being employed in receiver input waveguides in millimeter wave systems which are operating with collocated adjacent channel systems.

8. 6.7.3 Receiver Stability

It is recommended that receiver stability requirements of MIL-STD-469 be specified for millimeter wave receivers to assure compatibility with associated transmitters.

9. 6.7.4 Receiver Radiation

It is recommended that millimeter wave receiver radiation be limited to -30 dBm/meter^2 in the antenna main beam at the antenna focal point. This level is recommended as it represents a radiation field in the third antenna sidelobe which is in line with the radiated emission requirements recommended for the extended RE02 limits. The second side lobe should be at least 20 dB down from the main beam. No other millimeter wave systems can operate in the main beam due to the narrowness of millimeter wave antenna beams. This requirement shall not apply to transceivers since they exhibit the same antenna radiation levels when receiving as transmitting.

3. MIL-STD-461 Testing Requirements

Table 11 below contains the recommended extensions for MIL-STD-461A testing.

TABLE 11. MIL-STD-461A, NOTICE 4
EXTENSIONS FOR MM-WAVE SYSTEMS

MIL-STD-461 Test	Description	Applicable Systems	Recommended Extension
CE01, CE02, CE04	Conducted Emissions, 0.03 to 50 kHz, Power Leads	Type 1 required Type 2 and 3 tailored	None
CE03, CE05	Conducted Emissions, 0.03 to 50 kHz Signal/Control Leads	Type 1 required Type 2 and 3 tailored	None
CE06	Antenna Conducted Emissions 10 kHz to 10 GHz	None	None
CS01, CS02	Conducted Susceptibility	Type 1 required Type 2 and 3 tailored Class C tailored	None
CS03	Intermodulation	Type 1 and 2 Class A and B required Type 3 tailored Class C tailored	0.9f_{co} to 100 GHz only f_{co} = wave-guide cut off frequency
CS04	Rejection of Undesired Signals	Type 1 and 2 Class A and B Type 3 tailored Class C tailored	Same as CS03
CS06	Spike, Power Leads	Class A and B, Type required, Type 2 and 3 tailored Class C tailored	None
CS07	Squelch	All	None
RE01/RE04	Magnetic Field Emissions, 30 Hz to 30 kHz	Tailored	None
RE02	Electric Field Emissions 14 kHz to 10 GHz	All	See Figures 25 through 28

TABLE 11 MIL-STD-461A, NOTICE 4 EXTENSIONS FOR MM-WAVE SYSTEMS (Continued)

MIL-STD-461 Test	Description	Applicable Systems	Recommended Extension
RE03	Antenna Radiated Spurious and Harmonics, 14 kHz to 10 GHz	Type 1 and 2 Classes A and B required Type 3 tailored Class C tailored	10 to 100 GHz range only
RS01	Magnetic Field Susceptibility, 30 Hz to 30 kHz	None	None
RS02	Magnetic Field Induction	Tailored	None
RS03	Electric Field Susceptibility	Type 1 and 2 Class A and B required Type 3, tailored Class C tailored	Type 1 14 kHz to 100 GHz Type 2 10 to 100 GHz only 130 dB/uV/meter for 10 to 100 GHz

4. MIL-STD-469 Testing

Table 12 contains the recommendations for extension of MIL-STD-469 testing.

TABLE 12. RECOMMENDED EXTENSIONS FOR MIL-STD-469

MIL-STD-469 Paragraph	Description	Applicable Systems	Recommended Extension
6.2	Transmitter Frequency Tolerance	All	Tailoring of requirements recommended – further study needed
6.3	Maximum Emission Bandwidth	All	Modification for special techniques Proposed revision of Aug 1972 and OTP document are recommended
6.4	Tunability	Classes A and B required Class C tailored	None

TABLE 12. RECOMMENDED EXTENSIONS FOR MIL-STD-469 (Continued)

MIL-STD-469 Paragraph	Description	Applicable Systems	Recommended Extension
6.5	Antenna Side Lobe Suppression	All	None
6.6	Transmission Spurious Radiation	All	40 GHz to 100 GHz shaped spectral envelope – specified in antenna field
6.7.1	Receiver Acceptance Bandwidth	All	Same as 6.6
6.7.2	RF Preselection	None	Band pass filters where required
6.7.3	Receiver Stability	All	None
6.7.4	Receiver Radiation	All except transceivers	-30 dBm/meter^2 at antenna focal point

5. Millimeter Wave Test Requirement Matrix

Table 13 contains a list of recommendations for tests to be required or deleted for various modes of millimeter wave system operation.

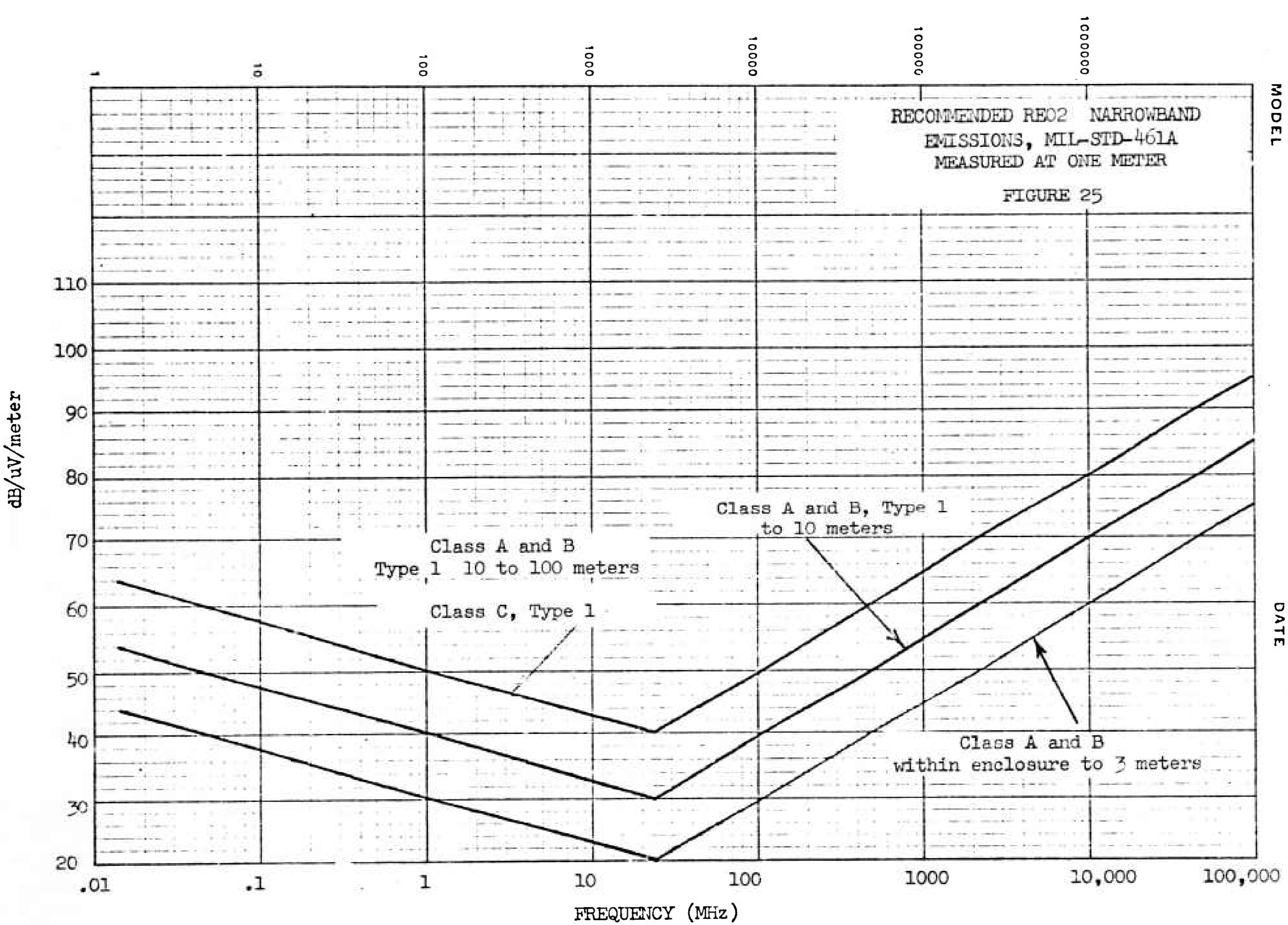
TABLE 13. MM-WAVE TEST REQUIREMENT MATRIX

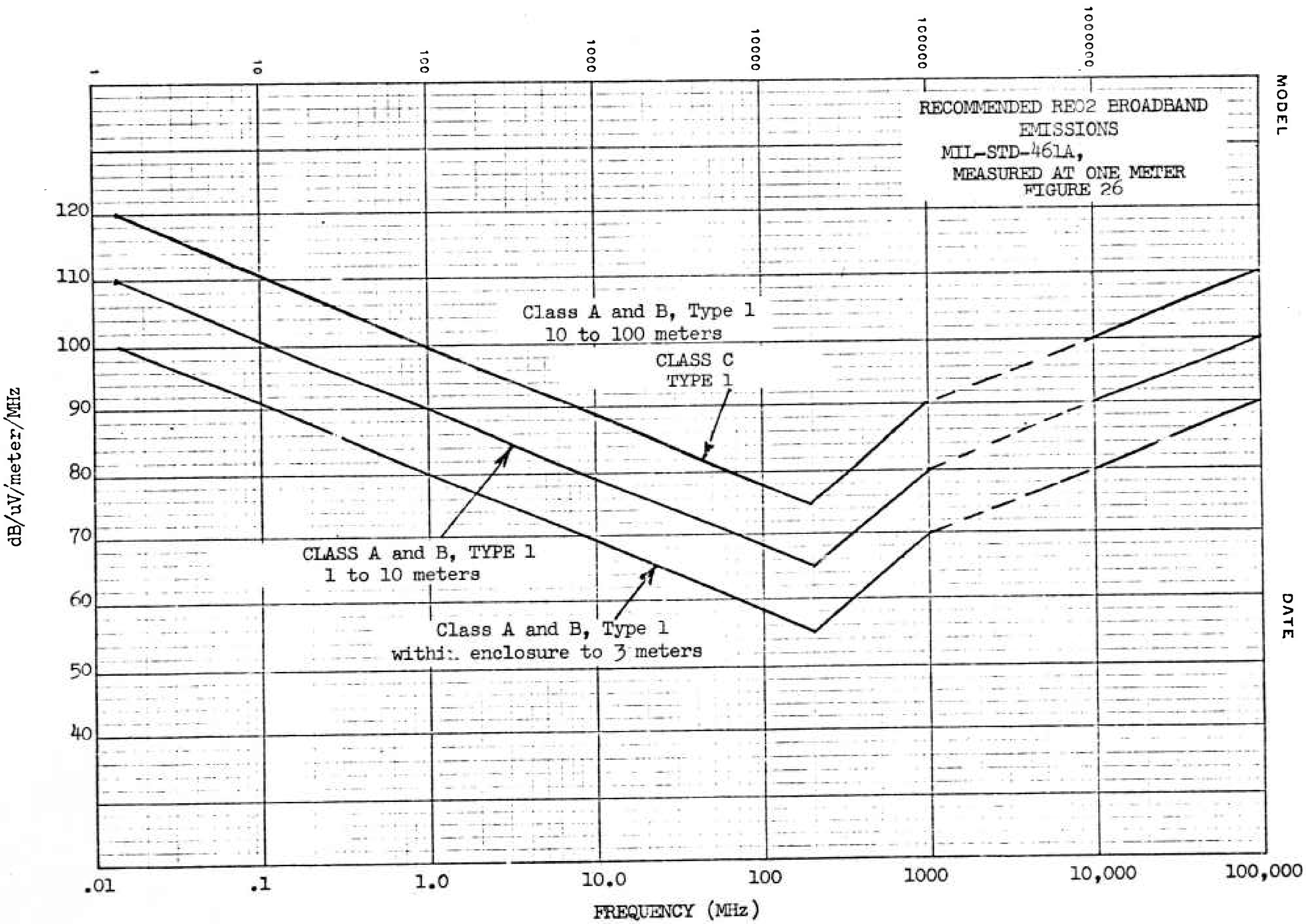
Test	Modes of Operation				Comments
	Receive	Transmit	Standby	*Acquisition	
ALL CLASSES OF SYSTEMS (MIL-STD-461 Type of Tests)					
Power and Signal Lines Conducted Emissions (CE01, CE02, CE03, CE04, CE05)	Test	Test	No Test	No Test	Limit upper test frequency to 50 MHz
Power Line Conducted Susceptibility (CS01, CS02, CS06)	Test	Test	Test	Test	Limit upper test frequency to 400 MHz
Radiated Emissions (RE01, RE02, RE04)	Test	Test	No Test	No Test	Limit upper frequency on RE01 to 30 kHz; RE02 tests over frequency range of 14 kHz to 100 GHz.
Antenna Emissions (CE06, RE03)	Test	Test	Test	No Test	Harmonic emission tests shall be limited to systems operating below 50 GHz
Radiated Susceptibility (RS01, RS02, RS03)	Test	Test	No Test	Test	Upper frequency limit of RS01 shall be limited to 30 kHz: RS03 shall be performed over the frequency range of 14 kHz to 100 GHz
Receiver Susceptibility (CS03, CS04, CS07, CS08)	Test	No Test	No Test	Test	Tests shall be performed over the frequency range of 0.9 fc. to 100 GHz
Electromagnetic Compatibility Test	Test	Test	Test	Test	Compatible operation of all systems shall be verified

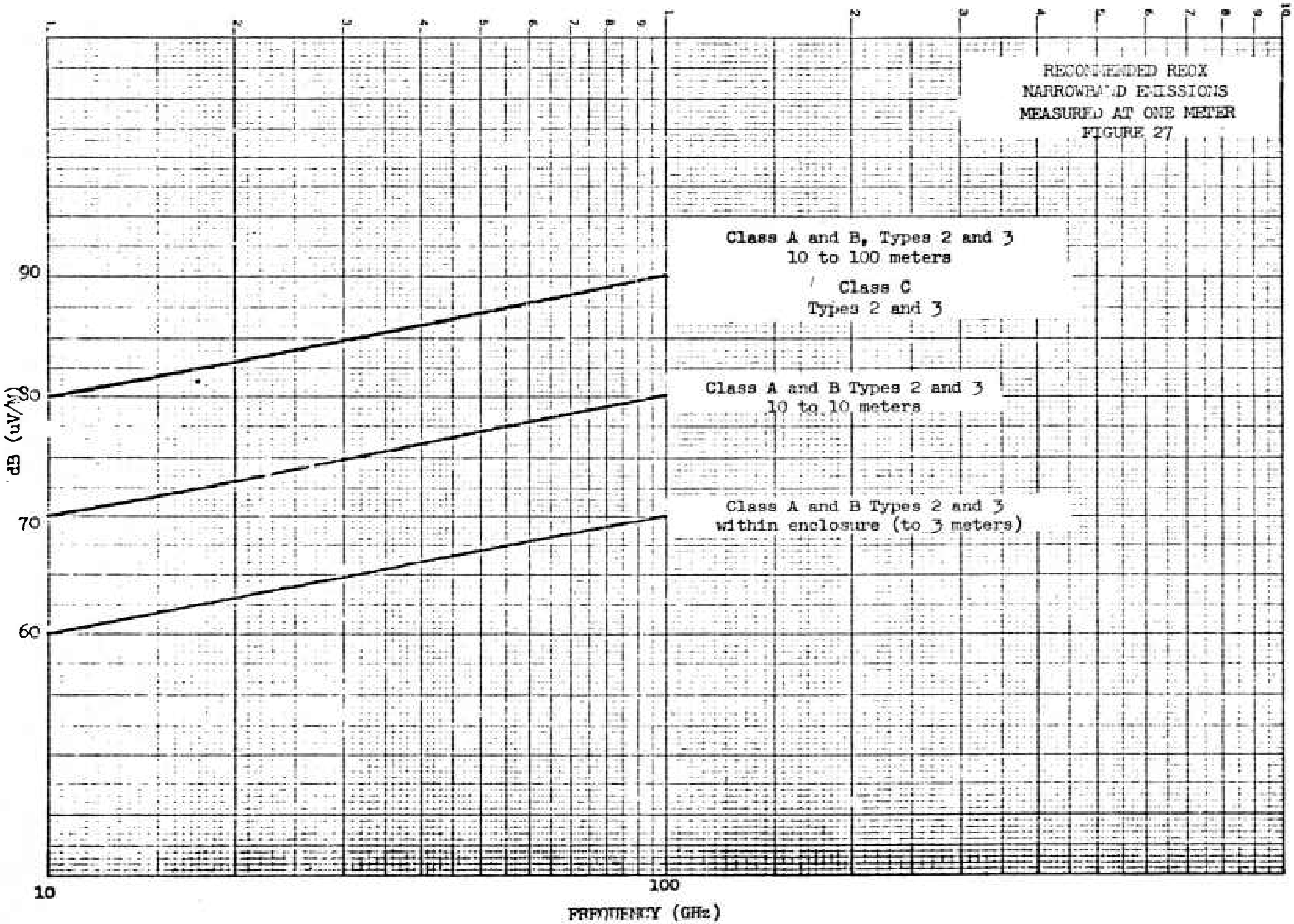
TABLE 13. MM-WAVE TEST REQUIREMENT MATRIX (Continued)

Test	Modes of Operation				Comments
	Receive	Transmit	Standby	*Acquisition	
RADAR SYSTEMS (MIL-STD-469 Type of Tests)					
Transmitter Frequency Tolerance	No Test	Test	No Test	No Test	Radar systems shall be subjected to these radar tests in addition to MIL-STD-461 type tests. All MM-Wave radar system compatibility tests shall include frequencies up to 100 GHz. Some areas need further investigation such as emission bandwidth, receiver acceptance bandwidth, frequency tolerance and receiver emission.
Transmitter Emission Bandwidth	No Test	Test	No Test	No Test	
Transmitter Tunability	No Test	Test	No Test	No Test	
Transmitter Spurious Emissions	No Test	Test	No Test	No Test	
Receiver Acceptance Bandwidth	Test	No Test	Test	No Test	
Receiver Radiation	Test	No Test	Test	No Test	
Antenna Side Lobe Suppression	Test	Test	No Test	No Test	

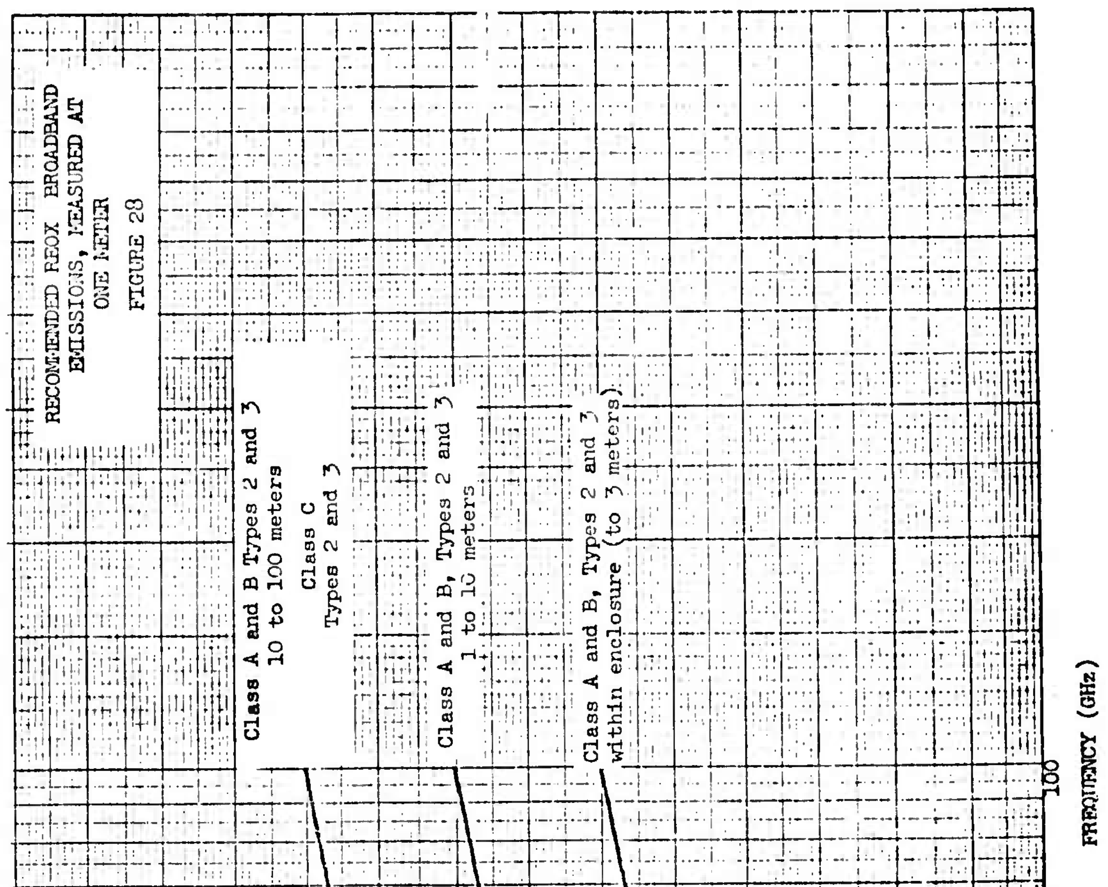
*Other modes may include lock - lock break and AGC capture.


MODEL
DATE
RECOMMENDED RE02 NARROWBAND
EMISSIONS, MIL-STD-461A
MEASURED AT ONE METER
FIGURE 25
1
10
100
1000
10000
100000
1000000
110
100
90
80
70
60
50
40
30
20
dB/uV/meter
.01
.1
1
10
100
1000
10,000
100,000
FREQUENCY (MHz)
Class A and B
Type 1 10 to 100 meters
Class C, Type 1
Class A and B, Type 1
to 10 meters
Class A and B
within enclosure to 3 meters


RECOMMENDED RE02 BROADBAND
EMISSIONS
MIL-STD-461A,
MEASURED AT ONE METER
FIGURE 26
MODEL
DATE
Class A and B, Type 1
10 to 100 meters
CLASS C
TYPE 1
CLASS A and B, TYPE 1
1 to 10 meters
Class A and B, Type 1
within enclosure to 3 meters
dB/uV/meter/MHz
FREQUENCY (MHz)
.01
.1
1.0
10.0
100
1000
10,000
100,000
120
110
100
90
80
70
60
50
40
1
10
100
1000
10000
100000
1000000



RECOMMENDED REDX NARROWBAND EMISSIONS MEASURED AT ONE METER
FIGURE 27



RECOMMENDED REOX BROADBAND EMISSIONS, MEASURED AT ONE METER

FIGURE 28

VII. CONCLUSIONS AND RECOMMENDATIONS

Reviewing the overall results of the study leads to the following general comments and recommendations.

A. CONCLUSIONS

1. Millimeter wave system components exhibit interference characteristics in specific areas which require close attention in obtaining interference-free operation. An example of this is the susceptibility of typical millimeter wave mixers to high level interference signals. Rigid quality control and the use of millimeter wave band pass filters represent control methods which should be implemented.

2. Millimeter wave systems in general exhibit less conducted susceptibility problems than lower frequency systems. This is due to the decrease in cable coupling at millimeter wave frequencies. Conducted susceptibility is limited to affects produced by modulation frequencies.

3. Upgrading of portable EMC instrumentation in the millimeter wave region is needed. Specific areas of required improvements include reduction of spurious responses, accurate frequency readout, built-in calibration and increased sensitivity.

4. Collocated low frequency systems should be evaluated for harmonic output as high as tenth order when deployed with millimeter wave systems.

5. Millimeter wave systems experience less interference problems than lower frequency systems in general. This is due to decreased coupling in cables, extremely narrow antenna beam widths, line of sight propagation, shielding by numerous types of matrices and low level case emissions.

6. Analysis of horn antennas performed in this study indicates that the effective gain decreases only slightly at the second and third harmonics. Further analysis of the numerous types of antennas employed proved to be beyond the scope of this contract.

7. Results of the experimental program indicates that previous extension of MIL-STD-461 which have been employed on millimeter wave systems such as in spacecraft represent reasonable limits for closely confined deployments. Relaxation of limits for more widely deployed systems has been addressed in this report.

B. RECOMMENDATIONS

1. Millimeter wave systems may be operated successfully in the main beam of collocated lower frequency systems providing operation is not attempted at exact harmonic frequencies up to the tenth order.

2. MIL-STD-461A, Notice 4 requirements can be reduced considerably for millimeter wave systems. Tailoring of low frequency tests of MIL-STD-461A is recommended when low frequency systems are planned for collocation with millimeter wave systems.

3. The possibility of imposing quality control in millimeter wave component parameters which affect interference characteristics should be considered.

4. Addition of bandwidth considerations to antenna emissions should be given further study both for present MIL-STD-461A limits and millimeter wave extension.

5. Millimeter wave reflection and shielding characteristics should be considered in deployments.

6. Millimeter wave systems should not be operated at locations which are nearer than the fourth sidelobe to the main beam of collocated millimeter wave systems. This represents an angle of only ±6 degrees in many cases.

7. This report has recommended rigid limits for millimeter wave systems which are closely confined in enclosures and relaxed limits for millimeter wave systems more widely deployed up to 100 meters.

8. Further studies of MIL-STD-469 requirements is suggested. Requirements such as the emission bandwidth are not presently stated in the proper context to represent modern radars in both millimeter wave and lower frequency applications. One example of this is the frequency agile type of radar. MIL-STD-469 requirements should be made more severe in certain areas such as frequency tolerance and out-of-band emissions.

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Electromagnetic Compatibility
Millimeter Waves

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of a 12 month study program designed to obtain data on millimeter wave system electromagnetic compatibility characteristics. The period covered is from 6 Feb 1974 to 6 Feb 1975. Results described in the first three quarterly progress reports (references 1, 2 and 3) are summarized. Activities of the fourth quarter are described and recommendations for requirements of the millimeter wave electromagentic compatibility specifications are included.

20. Abstract (contd)

The millimeter wave electromagnetic compatibility study was performed with the objective of obtaining data which can be applied in establishing an electromagnetic compatibility specification for millimeter wave systems operating in the frequency range of 10 to 100 GHz. The effort was designed to investigate millimeter wave EMC problems, to recommend electromagnetic interference reduction techniques and to update present military EMC specifications and standards to include millimeter wave systems.

An experimental program was conducted to collect data on EMC aspects of millimeter wave systems. This experimental program was designed to gather specific data which was found lacking in available millimeter wave literature which was reviewed during the literature search conducted in Phase I of the program. Data was collected on the levels and frequencies of spurious emissions, the relative levels of spurious response, radiated interference and radiated susceptibility. Millimeter wave coupling factors were investigated. These investigations included experiments on cable coupling and propagation, shielding and reflections of millimeter wave signals. Interference characteristics of modern state-of-the-art millimeter wave components were investigated.

Inter and Intra system EMC aspects of various millimeter wave systems were evaluated. Tests were performed to evaluate the unintentional electromagnetic interference characteristics of millimeter wave systems relative to other millimeter wave systems and other communications-electronics equipments and systems. The tests were designed to evaluate EMC between millimeter systems that may be located in the same enclosure and other systems that may be located within a radius of 100 meters.

An analysis program was conducted to support the experimental program. This analysis included the employment of a computer program to evaluate interference problems in typical millimeter wave system deployments. Other analysis consisted of an antenna out-of-band characteristic study, a millimeter wave filter study and a computer-aided spurious response analysis of typical millimeter wave receivers.

Recommendations submitted for specification limits were based upon the data and information collected during the study. These limits included such requirements as system radiated emissions and susceptibilities, transmitter spectra, receiver spurious responses, conducted interference and susceptibility, acceptance bandwidth and emission bandwidths. Recommendations were also made for testing methods and test instrumentation requirements.